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Review Article

Unlocking biogas production potential: Evaluating the environmental impact and biodegradability of pharmaceutical and medical wastes

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ABSTRACT

Addressing the pollution problems caused by improper disposal of effluents and wastes from pharmaceutical companies and medical facilities are important for the safety of humans and animals. This work highlights the challenges and developments in medical and pharmaceutical waste management practices across the world as well as their potential for bio-energy production. It involves the study of these waste properties, their impacts on the ecosystem and treatment or recycling methods. Various studies have shown that successes have been recorded in converting some antibiotic contaminated wastewater to biogas in advance anaerobic digesters. Moreover, not all medical wastes are degradable, the use of placentas, hospital cotton waste, human urine, waste blood and surgery waste has been used in biogas plants built at close proximity to hospitals, in some cases. However, such plants are few and are only located in Tanzania, India and Philippines, among others to generate biogas to power hospitals, boil hot water needed by patients and for cooking. This is because the level of awareness as regards the dangers associated with indiscriminate disposal of medical and pharmaceutical waste is low and hence the development of waste disposal policy by countries is often overlooked. The implication of this is the spread of diseases in affected areas which can results in epidemics. It is therefore necessary to formulate policies that allow the harnessing of these wastes to biogas/bioenergy or the creation of better waste management practices that is environmentally safe.

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INTRODUCTION

Wastes in general, can be categorized into easily degradable, hardly degradable or non-biodegradable materials. Pharmaceutical waste are unused, spilt, or expired drugs or vaccines that is itself an inhibitor in anaerobic digestion systems or in simple terms, 'hardly degradable' [1]. Pharmaceutical residues are harmful to natural water sources and are just 3% of medical waste; hence referred to as micropollutants [2–7]. They are found in water bodies due to common usage and manufacturing procedures caused by increased number of emerging pharmaceutical industries [8, 9]. In that sense, nearly, 10,000 liters of pharmaceutical wastewater is generated in India daily [10]. Their characteristics short-life, high organic load and high chemical oxygen demand (COD) makes them difficult to treat using neither physical, chemical or biological means [11–13]. Medical/clinical waste are of human and veterinary origins and includes body fluids, placenta, blood, sharp objects, culture dishes and pathological waste [7]. Anaerobic digestion, as one typical biological treatment process is favored by proteineous medical and pharmaceutical waste in different anaerobic reactors [14–16]. Presently, the effect of only few out of 3000 various medical and pharmaceutical residues in wastewater or pure form (e.g., penicillin bacterial residue) for biogas production has been analyzed [17, 18].

Biofertilizer, biohydrogen and biogas are three resulting by-products of pharmaceutical effluents and medical waste via AD, with near zero carbon emission [19–21]. The technology involves 3-4 intermediate biological decomposition steps and is carried out in fixed dome, balloon or tubular digester and floating drum bioreactors via wet or dry procedures, influenced by several factors [22–27]. Most importantly, pharmaceutical waste/effluents AD is enhanced using various types of microorganisms (e.g., bacteria, protozoa, helminths, microalgae and fungi) and is efficient when proper mixing technology is involved [28–30]. For instance, Clostridium plays an important role in the degradation of compounds containing cellulose and starch, Bacillus helps in the decomposition of proteins and fats and rhizosphere microbiota only degrade plant waste and organisms [23, 27, 31, 32]. Microalgae and blue-green algae (cyanobacteria) can be used in many ways. Namely, as food by humans, a potential pharmaceutical contaminant remover, heavy metal remover, in biofertilizer production by fixing nitrogen, bioplastic production and as biogas/biofuel/biodiesel/biohydrogen production ingredient [33–35]. Contaminants elimination using microalgae follows 3 mechanisms comprising of bioadsorption, biodegradation and accumulation [36]. Microalgal AD is suitable for biogas production as earlier affirmed by scientist since the 1950s [33]. Notably, the same author selectively degrades 9 antibiotics and 1 antidepressant (10 PhACs) at laboratory scale. In 1980s, potentials of fungi species numbering over 14,000 to digest pharmaceutical compounds in effluents, was proposed [37, 38].

An overview of biogas development from the past up to this present time shows that there has been rapid growth in the technology since 1920 in terms of its utilization for street lighting, cooking fuel and transportation fuel [20, 24]. A plant to digest agricultural, municipal and industrial waste, including medical and pharmaceutical wastes had been developed with set target for future multiplication in Skåne, Poland, Pakistan, Austria, Denmark, Turkey, Argentina, Sweden and other European nations [24, 27, 39–45]. Thus, precise aim of building these plants is to reduce organic waste pollution, deforestation, emission reduction and sustainable energy development. But Gittelson et al. [46] lists several reasons why biogas is not sustainable, arguing that the gas is highly toxic, flammable, potentially explosive and contains greenhouse gases which are released via combustion processes and diffusive emissions comparable to manures. The authors also maintained that, transporting biogas would require pipelines with exact problems faced with natural gas (such as leaks and emissions) which did not 'as believed' solve the emission issue it was designed to address. However, the new assertion hasn't been analyzed by scientist to challenge the continuous development of biogas plants across the globe. Moreover, apart from this technology, some wastes, especially of medical and pharmaceutical facilities would lie unattended to, thereby posing serious health issues to humans and animals. Hence, the general objective of this work is to review the pharmaceutical industry and related products and the treatment of wastewaters emerging from them. This work tries to study the dangers associated with medical and pharmaceutical waste in the ecosystem; their possible decomposability, by x-raying their previous exploitation for biogas generation; and the need for future research on these two wastes sources, as specific objectives. This was carried out by studying the pharmaceutical industry products and effluents and their pollution effects and the roles of different bioreactors in enhancing their conversion into useful products.

LITERATURE REVIEW

Pharmaceutical Industry

End-users of products from pharmaceutical companies including raw materials, veterinary medicine, antibiotics and cosmetics are humans and animals [47–49]. In pharmaceutical industries, large varieties of these products emanates from five manufacturing processes, namely, fermentation, extraction, chemical synthesis, formulation and packaging [50–52]. Any of these processes has the potential of generating wastewaters containing higher organic loads of harmful constituents to plant, human, animal and aquatic life [48, 50]. The chemical synthesis and fermentation categories of bulk pharmaceutical production process, produces higher volume of wastewater containing salts, recalcitrant organics, spent solvents and pharmaceutical residue (PR) [50, 52]. Currently, the world is witnessing

an increased growth in the pharmaceutical industry as core components of the chemical industry [53]. The pharmaceutical supply chain normally has four components, namely, the primary manufacturer, secondary manufacturer, distribution centers, and retail outlets (including hospitals and pharmacies) [54]. Majority of the globe's largest producers of pharmaceuticals are actively based in Ireland, where considerable amounts are also exported [55]. There are 250 multinational pharmaceutical companies all over India which is regarded as one of the largest and fastest growing industries [56–58]. Andersson & Karlsson [59] reported that, Sweden uses more than 1000 different active substances in about 7600 pharmaceuticals. First pharmaceutical industry in Nigeria was the May & Baker Nigeria Plc founded in 1944 – adding up to over 115 registered manufacturers in Nigeria which started in early 1960s [60]. However, due to high population figures in China, they are understandably, the highest manufacturer and consumers of pharmaceuticals globally [61]. Presently, the largest pharmaceutical company in South Africa, 'Aspen Pharmacare', was established in 1850; while 'Adcock Ingram', the second largest pharmaceutical firm in the country, trace its roots to 1890 [62]. Pharmaceutical products from Kenya often end up in Uganda, Burundi, DRC, Tanzania, Rwanda, Malawi, the Comoros and Ethiopia, among other destinations [63]. List of pharmaceutical companies in Kenya, Nigeria, Egypt and South Africa can be found in the literature [60, 63–65]. Pharmaceutical companies in Nigeria are located in Lagos, Ogun, Kano, Imo and Anambra states. However, the activities of some unregistered pharmacies in cities like Lagos, makes the garnering of accurate data of its usage in that part of the country difficult [66]. In 2021, revenues from pharmaceuticals was forecasted by WHO [67] to reach $1400 billion. North America accounts for 49% of the revenue, Africa, 0.7%, Europe, 21.8%, Asia-Pacific, 21.7%, Latin America, 4.6%, and Turkey, Middle-East-Eurasia 2.2%. In Africa, most of the pharmaceutical industries (representing 80%) are concentrated in just 8 countries (Egypt, South Africa, Algeria, Tunisia, Nigeria, Morocco, Kenya, and Ghana), according to a 2020 report which puts their sum at approximately 600 [68]. Experts predicts a further growth (from 2020 onwards) in pharmaceutical manufacturing in Africa from a value of $40-$65 billion – a growth trend that was maintained compared to 2013's worth of $20.8 billion [69]. Asplund [13] predicts that, the world's medicine market may go back to pre-pandemic levels in 2022, approaching almost $1.8 trillion by 2026.

Pharmaceuticals

Preferably, the main role of pharmaceuticals is to influence the function of human biological elements, especially their cells and also methanogens responsible for anaerobic digestion [70]. Pharmaceuticals are generally classified into antibiotics, tranquilizers, antiepileptic, diuretics, azole (fungicide), anti-inflammatory, human drugs, analgesics, illicit drugs, blood lipid regulators, beta-blockers, anticancer drugs, antirheumatic, personal care products (PCPs), psychotropic, cholesterol medicines, steroids and related hormones [13, 38, 71–74]. Some examples of pharmaceuticals of veterinary and human prescription, and hormones are paracetamol, rifaximin, sparfloxacin, sulfamerazine, ceftazidime, cilastatin, triclosan, β-estradiol, roxithromycin, minocycline, sulfisoxazole, androstenedione, megestrol acetate, ciprofloxacin, caffeine; chloramphenicol, clindamycin, danofloxacin, chlortetracycline, diclofenac, enrofloxacin, doxycycline, estriol, ethisterone, estrone, fenbendazole, sulfone, fenbendazole, ketoprofen, cloprop, clofibric acid, carbamazepine, ibuprofen, flunixin, florfenicol, ivermectin, marbofloxacin, lincomycin, metronidazole, ofloxacin, norfloxacin, oxytetracycline, sarafloxacin, sulfacloropyridazine, progesterone, fluoxetine, sertraline, sulfadiazine; sulfadoxine; sulfadimethoxine, clotrimazole, simvastatin, tamoxifen, sulfamethoxazole, sulfamazine, sulfathiazole, sulfaquinoxalin, tetracycline, testosterone, tilmicosin, and trimethoprim, among others [75–78]. Lincomycin ($C_{18}H_{34}N_2O_6S$) (LCM) is used to control gram-positive bacterial infection of human and animal and ranked second in 2012 in China in terms of consumption [61, 79]. LCM industries generates solid waste byproduct called lincomycin fermentation residues (LFR) containing residual LCM (whose concentration is around 2000 mg/kg), mycelial cells and different organic matters which can be degraded by black soldier fly larvae (BSFL) and associated microbiota [79]. Vultures and fish are reported to be gravely affected by some pharmaceuticals. In Pakistan, a study points at diclofenac residues as responsible for reduction of vulture population in the country, while mixtures of fluoxetine, ciprofloxacin and ibuprofen in g/L concentration range results in deaths of fishes [57].

Antibiotics Production and Uses

Being one of the most widely used pharmaceuticals, antibiotics occur in form of a compound or various array of molecules often channeled for the treatment and prevention of microbial infections in veterinary medicine and humans [47, 80]. In human and veterinary applications, there are about 250 different types of antibiotics [81]. Annually, China produces around 210,000 and consumes about 90,000 metric tons of antibiotics [61]. But according to Zhong et al. [17], in 2007, China produces 1.21 million tons of antibiotics, being the largest exporter and manufacturer in the world. Spain and Germany are the highest end-users of antibiotics within the European Union (EU) [82]. Hazardous waste such as antibiotic mycelial residues (AMRs) or antibiotic bioferment residues are produced in excess of 1.3 million tons in China, while 80,000 tons of veterinary antibiotics were used in 2013 in the same country [82, 83]. Consumption of veterinary antibiotics in 2013 in the United States was 11,000 tons, but global consumption of the generality of known antibiotics is still in thousands of tons [82, 84]. Mitchell et al. (2013)[85] stated that, of the 16,000 metric tons of antibiotics traded annually in the

country, approximately 80% are used in animal husbandry. Antibiotics are present in mixture form in the environment and are regarded as pollutants since they kill or inhibit the growth and development of microorganisms and aquatic animals [47, 86, 87]. Basically, they find applications in farming, human medicine, aquaculture and veterinary medicine, which end up in sewage or residues/excreta of poultry farms and livestock, causing heavy loses of microorganisms used in aerobic and anaerobic active sludge for effluent treatment [73, 84, 87]. Ofloxacin is an example of synthetic antibiotics widely used in aquaculture [70]. For instance, the antibiotics used as feed additives, therapeutic animal treatments, growth promoters and those used to prevent infections in pig farms can be excreted unchanged to the ecosystem [88]. This is the reason some veterinary pharmaceuticals are found in manures of some animals which contaminates the soil as well as ground and surface waters as a result of runoff from fields [89, 90]. Therefore, the digestion of some categories of antibiotic-contaminated cattle faeces or dungs is affected, as active methanogens are inhibited [91].

Few examples of antibiotics are amoxicillin, nitrofurantoin, gentamicin, rifampicin, doxycycline, tylosin, neomycin, erythromycin, sulfamethoxazole (SMX), tetracycline, roxarsone, carbadox, monensin, ofloxacin, streptomycin, flumequine, ciprofloxacin, bambermycin, apramycin, bacitracin, spectinomycin, oleandomycin, tiamulin, efrotomycin, trimethoprim, LCM and penicillin [23, 73, 92]. Erythromycin ($C_{37}H_{67}NO_{13}$), a macrolide antibiotic that emanates from *Saccharopolyspora erythraea* (or actinomycete), sulfamethoxazole (SMX), tetracycline, fluoroquinolones, ciprofloxacin (CIP) and enrofloxacin (ENR) are the most widely used human and veterinary antibiotics pausing as pollution threats to the environment [31, 47, 93–95]. An original form of erythromycin derivative called clarithromycin can be discharged unavoidably to the environment through human and animal excretion as it is not absorbed or utilized fully by the patient animal or human [96]. Clarithromycin utilization doubled to 15 tons per annum from 2002 to 2009 in Germany [96]. Erythromycin and tetracycline both inhibit protein synthesis while tetracycline forms complexes with ions present or bind to soil particles, where in 2018, 25% was used in veterinary medicine accounting for 33% of antibiotic consumption in 2012 in Europe [95, 97, 98]. SMX is basically a sulfonamide (SAs) bacteriostatic antimicrobial antibiotic used to arrest urinary tract infections, as it inhibits bacterial proliferation; as well as to prevent or treat mastitis in cattle and respiratory infections when combined with trimethoprim [86, 99–101]. But SAs, tetracyclines, β-Lactams, macrolides, fluoroquinolones and nitroimidazole derivatives are the most prescribed antibiotics in animal husbandry veterinary pharmaceuticals with a share use of 90% in the UK, 77% in the EU and above 50% in Denmark and Korea [91, 97, 102]. β-Lactam residues are hardly spotted in dairy manure compared to tetracycline residues that is persistent and common [103]. SAs, lincosamide, and macrolide residues, according to the same author is typically below 1 ppb in US dairy manure samples measured. SAs utilization in Germany is up to 9% and 2-11% in Europe, among which high amount of sulfadiazine (an SAs group) was detected in chicken and pig manure [97]. Visca et al. [93] reported that, SMX (which is quite mobile) at initial concentrations of 4-20 mg/kg in the soil, would half within 4-13 days. Tetracycline kills microorganisms by terminating protein synthesis after binding to the cell ribosomes, while other sub-classes such as oxytetracycline (OTC) and chlortetracycline (CTC) helps in improving health and growth efficiency when used in animal feeds, as well as for therapeutic purposes [23, 104, 105]. Tetracycline, CTC, and OTC (first isolated in 1940s) are cheap and measured at concentrations of ≈ 5, 10, and 250 μg/kg respectively in dairy manure [23, 103]. OTC, CTC and ENR are persistent veterinary antibiotics in the environment that is used in livestock farming [23, 106]. ENR is usually administered orally to cattle or by subcutaneous injection to treat alimentary tract and respiratory infections [93]. Both fluoroquinolones and CIP has high affinity for soil and persist for several months in the environment [93].

Amoxicillin belongs to the penicillin class and can be used to treat gastro-intestinal veterinary infections [91, 107]. An oral drug known as cephalexin in conjunction with cephaloglycin is used in treating diseases caused by gram-negative bacteria [108]. The outer membrane of gram-negative bacteria makes them more resistant to antibiotics, because it thwarts their penetration into the cells compared to gram-positive bacteria [109]. However, both cubical gram positive and circular gram negative forms of bacteria are killed by amoxicillin along with anaerobic bacteria as stated by Nuengjamnong et al. [110]. Hitherto, more than 700,000 deaths per year is said to be a result of antimicrobial resistance globally, and further estimates put this figure at 10 million by 2050 [31, 77]. Practical occurrence is at Puri (Bay of Bengal), India, in which previous investigations indicates the presence of 38 multi-resistant bacteria [105]. Based on experience and as stated by Oliver et al. [103], antibiotic-resistant bacteria (ARB) are present in dairy manure.

Pharmaceutical Effluent

The poor biodegradability of pharmaceutical plants' wastewater or effluent is due to large compositions of inorganic and organic toxic pollutants (such as intermediate products, catalysts, spent solvents, additives and reactants), high salt concentration and its characteristic dark color, despite having higher chemical oxygen demand (COD) and a low biochemical oxygen demand (BOD) [63, 111–116]. BOD and COD in wastewater can be determined using procedural steps illustrated by Njuguna et al. [63]. The pH of pharmaceutical effluents ranges from 4-11 while its salt content (e.g., chlorides, bromates and sulfates) could be above 1 g/L [117, 118]. Therefore, pharmaceutical industry wastewater comes from chemical synthetic plants

whose constituents are complex and pose serious risk to the ecosystem by inhibiting active biomass even at negligible amounts [53, 111, 119]. The high COD level in the toxic effluents is normally reduced using a chemical treatment technique called wet oxidation: which is defined as the transfer of one or more electrons from a reductant (an electron donor) to an oxidant (an electron acceptor) having higher affinity for electrons [11, 53, 120]. Otherwise, the wastewater discharged from pharmaceutical industries are difficult to treat because of the variable character the constituent toxic compounds possess [11, 121–123]. Above all, treatment of chemical synthesis-based pharmaceutical effluents involves a lot of complex operations due to formation of chemical reactions in the process [122]. Notwithstanding its characteristic high COD level, anaerobic treatment is generally favored [111]. A starting specimen for formulating commercially vital amoxicillin and ampicillin or 6-Aminopenicillanic acid (6-APA) are pollutants commonly found in the chemical synthesis and fermentation class of pharmaceutical wastewaters [107]. Others, as investigated in Kocaeli Province (Turkey) chemical synthesis pharmaceutical industry effluents by Gulmez et al. [122], are solvents such as isopropanol, methylene chloride, tetrahydrofuran, ethyl acetate, pyridine, methyl isobutyl ketone and methyl ethyl ketone, used at different production stages. Examples of wastewaters of pharmaceutical industry sources from manufacturing processes are azalide antibiotic raw water, azalide antibiotic pre-treated water, broad spectrum tetracycline antibiotic raw water, diuretic production raw water, disinfectant chlorhexidine-dihydrochloride raw water and molasses slops raw water [119]. It is however obvious that pesticides and some micropollutants are not scrutinized for potential environmental effect in the literature compared to drugs like analgesics, antituberculosis, antibiotics and antihistamines despite their utilization on the same scale [89, 124].

Environmental Contamination

Pharmaceutically active compounds (PhACs), about 2300 active pharmaceutical ingredients (API) and pharmaceutical wastewaters are anthropogenic contaminants that affects human health and the ecosystems when released into the surrounding environment above certain concentrations; because they contain high COD due to the presence of organic and inorganic constituents [105, 125–128]. In such plants, wastes or effluent disposal is subject to further processing in pharmaceutical wastewater treatments plants (WWTPs), which is not often the case because half of the pharmaceutical wastewater generated globally are discharged without prior treatment as reported in the literature [127, 128]. Zhan et al. [129] describe pharmaceutical process residues (PPR) as herbal and antibiotic fermentation residues. Numerous pharmaceutical residues are practically unaffected or barely removed even after passing through WWTPs [126, 130]. In addition, non-industry pharmaceutical wastes released to the environment are as a result of prescriptions (veterinary medicinal products) taken by humans and animals which are often excreted with faeces and urine in its original form (or parent substances) [73, 131–133]. Typical instances are the detection of LCM (7820 mg/L) in swine manures and 3 swine farms aqueous wastewaters (166 mg/L) in China due to intense application [61].

Researchers across the globe have detected several PhACs and PCPs in soils, ground water, drinking water supplies, sea water, surface water (lakes, rivers, and streams), municipal wastewater, wastewater treatment plants effluents and slaughterhouse wastewater, with detrimental effect to livestock, aquatic life and human health even at low concentrations (sludges) [50, 57, 73, 81-82, 130-131, 134-136, 137, 138,]. However, Alenzi et al. [92] attributed this to huge demands for medicines by users on daily basis. Concentrations of these micropollutants (pharmaceutical compounds) vary from ng/L to μg/L in natural water bodies and domestic effluents to up to mg/L levels in streams [77, 81, 86, 139–141]. Notable drugs or PhACs that have been detected in dirty water, soil and garbage are pivalic acid, 2-ethylhexanoic acid (2-EHA), antiepileptic drug carbamazepine (CBZ), vitamins, antidepressants, sleep aids and narcotic pain relievers to mention a few [121, 140, 142, 143]. Moreover, 80 persistent pharmaceuticals and medical substances (such as cytostatic drugs, clofibrate, antibiotics and analgesics) have been spotted in drinking water, sewage, sewage treatment plant wastewaters, surface and ground waters of about 10 countries, since 1980s as described by Nguluka et al. [57] and Fountoulakis et al.– while 200 different others are found globally in river waters according to Alenzi et al. 92]. The manufacturing, trade, storage and use of 12 persistent organic micro-pollutants (POPs) had earlier been restricted at a global treaty Stockholm Convention to safeguard the ecosystem [144]. The POPs covered are chlordane, aldrin, dieldrin, DDT, endrin, hexachlorobenzene, heptachlor, mirex, polychlorinated biphenyls, polychlorinated dibenzofurans, polychlorinated dibenzo-pdioxins, toxaphene, beta hexachlorocyclohexane, alpha hexachlorocyclohexane, chlordecone, hexabromobiphenyl, commercial octabromodiphenyl ether (hexabromodiphenyl ether and heptabromodiphenyl ether), pentachlorobenzene, lindane, perfluorooctane sulfonic acid (PFOS), its salts and perfluorooctane sulfonyl fluoride (PFOS-F).

Notable PhACs Pollution

Canada, USA, Brazil and many European nations found over 80 drugs in their aquatic ecosystems – UK alone detects 70 [92, 145]. This includes up to 83 ng dm^{-3} of paracetamol (in groundwaters) in the vicinity of Gdańsk [98]; a 1994 discovery of clofibric acid in Berlin (Germany) surface waters [146], around 0.3-19 ngL^{-1} concentration of clofibric acid in North Sea, and approximately 100 ngL^{-1} in estuaries, both in UK [105], and as well as in the 1970s in WWTPs samples in the USA [145]; 1.7g/l concentrations of antibiotics in surface waters according to United States

Geological Survey (USGS) [90] and; 28-31 mg/L of ciprofloxacin in India's treated effluents and natural water bodies as well as UK, USA and Germany in the range of ng/L to g/L [57], to mention a few. Again, 3800 µg/L of metaxalone (a muscle relaxant), according to Colella [147], are found in New York's pharmaceutical manufacturing wastewaters. Clotrimazole in concentrations ranging from 3-54 ng/L are present in Germany and UK ecosystems, as reported by Pavithra et al. [105]. The same authors also position the presence of diclofenac concentrations at around 2.3 µg/L in UK pharmaceutical effluents. Propranolol, carbamazepine and ibuprofen had contaminated Doñana Park in Spain, whereas in Warsaw, Poland, clindamycin in concentrations of 134 ng/L have been found in influents pharmaceutical treatment plants [74, 78].

According to literature, analysis of dams, hospital effluent and sachet waters in Nigeria shows the presence of some antibiotics in alarming proportions. Usuma dam [148], which delivers treated water to Nigerian capital territory for instance, contains metronidazole, trimethoprim, ciprofloxacin, ibuprofen and amoxicillin whose risk levels are classified into low, medium and high to aquatic species, according to Ilechukwu [149]. Previous reports show high proportion of amoxicillin (8066 µg/L) in Sango Ota, Ogun state in Nigeria which has few pharmaceutical companies and whose population largely depends on the antibiotic [150]. Similar studies reveal the presence of 34.31 µg/L of acetaminophen in Ahmadu Bello University Teaching Hospital (ABUTH) samples of the hospital plant's wastewater treatment effluent in Zaria, Kaduna state and 2.57 µg/L of the same pharmaceutical product in irrigation wells in Sango Ota, a pharmaceutical industrial area in Ogun state in the country [150]. Nigerians presumed sachet water as 'pure' and so is taken in every state in the country. However, detection of some pharmaceuticals in Ogun and Lagos sachet water can be attributed to several functional industries in those areas and so should be a health concern for food safety bodies and regulators in the country [149]. Analysis of wastewaters in Kenya points to high concentrations of ibuprofen (26.54 mg/L), ciprofloxacin (14.98 mg/L), norfloxacin, sulfamethoxazole (62.83 mg/L), metronidazole (29.92 mg/L), paracetamol, trimethoprim (208.30 mg/L) and zidovudine [63]. In Machakos, 49,300 ng/L of sulfamethoxazole and 2800 ng/L of norfloxacin in Kangemi cities in Kenya has been detected in influent waters as well as many other pharmaceuticals in Nairobi River Basin in the country [78, 150]. According to literature, 8430 ng/L of trimethoprim is concentrated in influents wastewaters in Kampala, Uganda, 1193 ng/L of erythromycin in Choutrana, Tunisia, and 88,012 ng/L of ciprofloxacin, 20,656 ng/L of metronidazole and 5742 ng/L of ofloxacin are found in Durban in South Africa [78].

Frascaroli et al. [78] collectively reports concentrations of pharmaceuticals such as azithromycin (115,413 ng/L), clarithromycin (6917 ng/L), oxytetracycline (1531 ng/L), roxithromycin (19,135 ng/L) in Sanya – as well as tetracycline (374 ng/L) and sulfadiazine (574 ng/L) in Xinjiang cities in China high-strength wastewaters. LCM of concentrations between 3000-9000 mg/L in fermentation broth are said to be discharged from manufacturing facilities in the same country [61]. Studies had shown the occurrence of ibuprofen, propranolol and carbamazepine in Yangtze Estuary in China [74]. Collectively, Zhu et al. (2021)[61] stated that, roughly, 2200 metric tons of pharmaceutical effluents are released from production centers in the country.

Pharmaceutical Wastewater Treatment

There are three processes applied by wastewater treatment experts to disinfect it for public use and environmental protection, and they include physical, chemical and biological methods, which is further divided into preliminary, primary, secondary, tertiary and advanced treatment processes [13, 151–153]. In the pharmaceutical industry, two biological treatment techniques is used to treat an effluent of pharmaceuticals manufacturing origin, which is aerobic and anaerobic [47, 154-155]. Typical dual combinations of the biological processes is at the Brazilian wastewater treatment plants employing a hybrid units of anoxic, aerobic and anaerobic techniques [77, 156]; the one investigated by Inanc et al. [157] using aerobic-anaerobic techniques to disinfect a chemical synthesis-based pharmaceutical plant byproduct and; the successful toxic and organic matter removal from pharmaceutical effluent that is composed of nitroaromatic compounds using sequencing batch biofilter, which are known for combining the two technologies [158]. Alternatively, the sole use of anaerobic treatment method have been characterized with less energy consumption and high efficiency in treating high-strength pharmaceutical effluents, making it convenient for sludge digestion [153, 159-160]. Though it has the disadvantage of longer start-up time owing to low methanogens growth rate, it is still the most promising technique compared to the aerobic process which gained popularity in the 1960s [16, 121], and under which several innovations has been done to advance the technology. Currently, power is generated by anaerobic decomposition of sewage sludge in 146 UK facilities, amounting to 66% of all municipal sewage sludge in the country [80]. In the past, Schlott et al. [161] produced a design, erection and start-up of an anaerobic treatment scheme for pharmaceutical waste, whereas Murugesan et al. [162] happily shares the development in utilizing the process in Netherlands at the moment. Almost all anaerobic digestion plants are operated at mesophilic temperature regime – so even when typical influent temperatures received are less than 18°C, 30% of energy is expended to heat it prior to treatment, according to Enright et al. [55]. Therefore, a cost-effective option is psychrophilic anaerobic digestion (PAD) occurring at temperature less than 20°C. Activities of methanogens are significant in this process, and so the measure of the specific methanogenic activity (SMA) highlights the activity of the organism

in pharmaceutical wastewater being digested in bioreactors [55, 70, 90, 128]. Again, the digestion of some pharmaceutical wastewater containing high level of sulphate is reduced to sulphide by sulfate-reducing bacteria, also responsible for hydrogen sulphide generation in anaerobic bioreactors [16, 23, 111]. But since 1970, better significance is attached to a treatment option called anaerobic biofilter because of its advantage over the two conventional oxygen-related methods for toxic elimination from pharmaceutical effluents [121].

Pharmaceutical sludge has complex compositions, bad odor, and is highly corrosive due to the presence of salts, suspended solids, pathogenic microorganisms and refractory antibiotics (e.g., aureomycin, benzylpenicillin, berberine hydrochloric, colistin sulphate, ofloxacin, etc), with imminent danger to the environment if not properly treated before discharge [95, 115, 163–165]. Even though pharmaceuticals exist in low amounts in surface waters and domestic raw water, it rivals hospital and pharmaceutical dirty water which has higher concentrations (≅ 100–500 mg/L), in terms of their persistence and toxicity [30, 47, 74, 94, 166-167]. Consequently, high antibiotic levels in wastewaters is difficult to purify or remove and as such, genetically modified strains of microorganism is endorsed to treat such antibiotics contaminated effluents [87]. The term 'pharmaceutical removal' as used here, implies the loss of the parent compound via physical, chemical, bio-decomposition and sorption to solid organic matter [73, 168]. Classically, to achieve this objective, 4 kinds of sewage sludge can be recognized and treated in pharmaceutical wastewater treatment plants, namely, primary and secondary (called mixed sludge), aerobic/anaerobically fermented and dehydrated sludge, using landfill, incineration and biodegradation technique [127, 165, 169-171]. Both aerobic and anaerobic process and landfill is proven as ineffective technique in pharmaceutical sludge treatment, and as such, a burden in Europe that produces 15 million tons of sludge in 2021 alone [127, 165]. Practical basis is drawn from non-removal of carbamazepine, ciprofloxacin and triclosan containing PhACs in sewage sludge using aerobic and anerobic means according to Mejías et al. [127]. The same author refer to PhAC removal from sewage sludge as time-dependent, giving that it took doxycycline and tetracycline 77 days to be slightly removed. Affirmed that some bacterial strain can be used to degrade ciprofloxacin from pharmaceutical wastewater.

Advance chemical oxidation process (AOP) is a method known to increase treatment efficiency of industrial wastewater and promote its biodegradability [11, 172]. The process involves oxidation with oxygen at 200–300^{o}C and the use of energy oxidants (e.g., peroxone, hydrogen peroxide, sulfate radical, photons, and/or ozone) [11, 73, 173-174]. Ozone can be used to break down pharmaceuticals in water, but is however energy intensive and costly [11]. Ozonation is also a COD and color remover from wastewater [38, 112, 175]. Biodegradable nanoparticles can also be used to detect contaminants in water for its purification [176]. In addition, Zhang et al. (2022)[177] draws the attention of researchers to biological nitrogen removal from pharmaceutical dirty water, being an inhibitor and a bio-toxic. Alternatively, pollutants in sludge can be eliminated using biochar/activated biochar; especially caffeine which is a common pharmaceutical wastewater contaminant, as well as the use of biogas residue biochar to adsorb tetracycline [178–181]. Other progress in this direction includes the utilization of *Washingtonia robusta* to remove improved pollutants and heavy metals from pharmaceutical wastewater by Al-Samrraie et al. (2022)[182], tea-based materials and coffee utilization to remove pharmaceuticals in contaminated water, reviewed by Madikizela & Pakade (2023) [183], the use of hybrid constructed wetlands [184], and the use of air and pure oxygen to treat pharmaceutical industry wastewater, researched by Gnanavel & Muthusamy (2018).

Roles of Anaerobic Treatment Reactor Types

Several anaerobic reactors of unique configurations were previously studied for pharmaceutical wastewater treatment in the literature [16, 24, 47-48, 50–52, 77, 86, 94, 99, 107, 111, 115, 121-122, 128, 157-158, 185–194]. They include, anaerobic contact reactor (ACR), anaerobic baffled reactor (ABR), anaerobic batch reactor, anaerobic filters, anaerobic fluidized bed reactor (AFBR), anaerobic fixed film reactor (AFFR), anaerobic fluidized membrane bioreactor (AFMBR), anaerobic bio-entrapped membrane reactor (ABEMR), anaerobic membrane bioreactor, anaerobic mesophilic fixed film reactor (AMFFR), anaerobic plug-flow reactors (APFRs), anaerobic structured bed biofilm reactor (ASBBR), aerobic/anaerobic sequencing batch reactor (ASBR), anaerobic suspended film contact reactor (ASCR), anaerobic thermophilic fixed film reactor (ATFFR), anaerobic up-flow packed bed reactor, biofilm airlift suspension reactor (BASR), continuous stirred tank acidogenic reactor, electrochemical membrane bioreactors (EMBR), expended granular sludge blanket (EGSB), fluidized bed reactor (FBR), hybrid up-flow anaerobic sludge blanket (HUASB) reactor, modified internal circulation (MIC) anaerobic reactor, up-flow anaerobic bio-filter process (UABP), up-flow anaerobic filters (UAF), up-flow anaerobic hybrid reactors (UAHR), up-flow anaerobic sludge blanket (UASB), up-flow anaerobic stage reactor (UASR), and up-flow bio-electrochemical system (UBES). The treatment occur via some processes including stripper columns, coagulation, microfiltration, photocatalysis, sonolysis, Fenton/photo-Fenton process and reverse osmosis [8, 172, 195-196].

Commonly, WWTPs are not efficiently designed to remove micropollutants many of which are adsorbed to sludges, so that pharmaceutical drugs elimination is rarely complete [145]. But reactor technologies like ASBR, UASB, AMBR and MBBR are considered a new development even if they still have their challenges to effectively get rid of high resistant antibiotics for high biogas recovery [197].

Anaerobic fixed-film fixed-bed reactor is more efficient in removing organics and is best suited for pretreating herbal pharmaceutical effluent having high concentrations of organics [198]. ASBR (as shown in Figure 1) demonstrates a better treatment of pharmaceutical wastewater containing ≅ 40 mg/L of SMX; where above this limit, the reactor is disrupted leading to its failure, substrates utilization is inhibited and biogas production is affected [52]. Practically, Aydin et al. (2015)[95] studied the treatment of five synthetic pharmaceutical wastewater containing each of sulfamethoxazole–erythromycin–tetracycline (ETS), sulfamethoxazole–tetracycline (ST), erythromycin–sulfamethoxazole (ES) and erythromycin–tetracycline (ET) for 360 days inside an ASBR. UASB is basically a methane producing digester or an advanced type of clarigester that is widely applied owing to their low cost, ability to resist pH and temperature fluctuations, microbial diversity, and large biomass retention [162, 187]. Sreekanth et al. (2009)[128] studied the HUASB reactor using a terbinafine hydrochloride pharmaceutical effluent from Hyderabad with pH of 7-7.5 and BOD:COD ratio of 0.45-0.6. Likewise, the UAHR configuration combines the merits associated with both UAF and UASB, while limiting their disadvantage, making it effective in treating medium-to-high strength wastewater at high loading rates and short retention time [162]. UASR design separates the acidogenesis and methanogenesis stages, allows rapid recovery from hydraulic and organic shock loads, reduces biomass washout and needs no gas or sludge separation equipment, thereby demonstrating identity with ABR (consisting of UASB bioreactors connected in series) [52].

AMBR process amalgamates membrane separation and anaerobic biological treatment [111, 134, 160, 199]. Its benefits are low energy demand, less sludge production, enhanced biogas recovery, longer solid retention time, shorter hydraulic retention time, rapid start-up of microbial processes and a novel approach for treating effluents with variable flow, high COD and salinity content, suspended solids and inhibitory compounds (e.g., oil, fat and grease) [31, 73, 159]. But occasionally, different behaviors are noticed. For instance, even at high sludge retention period, reports presented by Cha et al. [142] shows that CBZ removal using the MBR technology was ineffective. A retention time of 435 days in an AMBR have also been reported – typically, pharmaceutical wastewater containing β-lactams antibiotics (BLAs) had been operated for 253 days in a 180 litres reactor [30, 159]. In another study, slow-growing anammox microorganisms was retained using an AMBR which boosted its activity 19 times [193]. Xiao et al. [200,201] investigate the removal of 5 PhACs in a bench-scale AMBR used to treat synthetic sludge. Pharmaceuticals like carbamazepine [13] and hydrochlorothiazide shows inefficient removal in activated sludge process (ASP) and MBR system. On the other hand, the advanced technology of the EMBRs are more efficient compared to ASPs and MBRs due to their low energy requirement [73]. Again, the novel ABEMR have superior merits over AMBR in terms of optimum organic removal and methane yield during pharmaceutical wastewater treatment [189]. However, problems with advanced technologies are limited applications (only at bench and pilot scales), membrane fouling, costly membrane materials and high energy needs [73].

EGSB is the modified but similar version of the UASB and UABP are used for treating high-strength pharmaceutical wastewater despite the problems associated with its use such as poor biomass retention, longer start-up caused by slow-growing microorganisms and inability to output solid-free effluent [162, 189]. Hu et al. 197] studied the performance of a novel UBES for the removal of β-lactams pharmaceutical effluents under different hydraulic retention time. The use of PAM as flocculant during wastewater removal from pharmaceutical factory workshop and after adding 200 mg/L of calcium chloride coagulant significantly neutralizes the effluent [143]. Though[105] affirms that electrocoagulation is 20 times more efficient compared to chemical coagulation. Previously, Mestre et al. shows that the novel powdered activated carbon and pine nut shell can be used to adsorb pharmaceutical compounds while Baaloudj et al. [202] proposes a technique for using sillenite ($Bi_{12}TiO_{20}$-BTO) catalyst to clean pharmaceutical wastewater composed of hazardous cephalosporin. Zero channeling of flow, compact bioreactor volume, recycle flow influent concentration dilution, uniform mixing resulting in high conversion rate, long biomass retention and high mass transfer rates are the advantages fluidized bed bioreactors offer during fungal treatment of wastewater [3, 38, 203].

A review on the use of conventional and nonconventional reactor systems to treat pharmaceutical effluents and produce biogas is shown in Table 1.

Medical Waste

Medical waste is basically all wastes generated from health facilities like dispensaries, medical centers and general hospitals, as a result of medical treatment, scientific research, diagnosis, immunization of humans or animals and/or therapeutic procedures such as injections, biopsy, resection of gangrenous organs, surgery, para-clinical exams, dialysis, delivery and autopsy [205–209]. The hospital could be tagged as an important source of pharmaceutical to the ecosystem which represents a small fraction of residue generated from typical municipality [147, 207, 210-211]. Medical wastes could be classified into infectious waste, hazardous waste, sharp waste and toxic waste which falls under two categories of risk and non-risk waste [7]. WHO report has it that 85% of hospital wastes are non-hazardous and the remaining 15% which is toxic is broken down into 10% hazardous (or infectious) waste, and about 5% non-infectious but hazardous (e.g., radioactive, chemical and pharmaceutical) [207, 212, 213]. But, based on literature report, other countries generate 10-25% of hazardous medical waste above the WHO report and 75-90% of such waste are non-hazardous [214, 215]. Longe & Williams

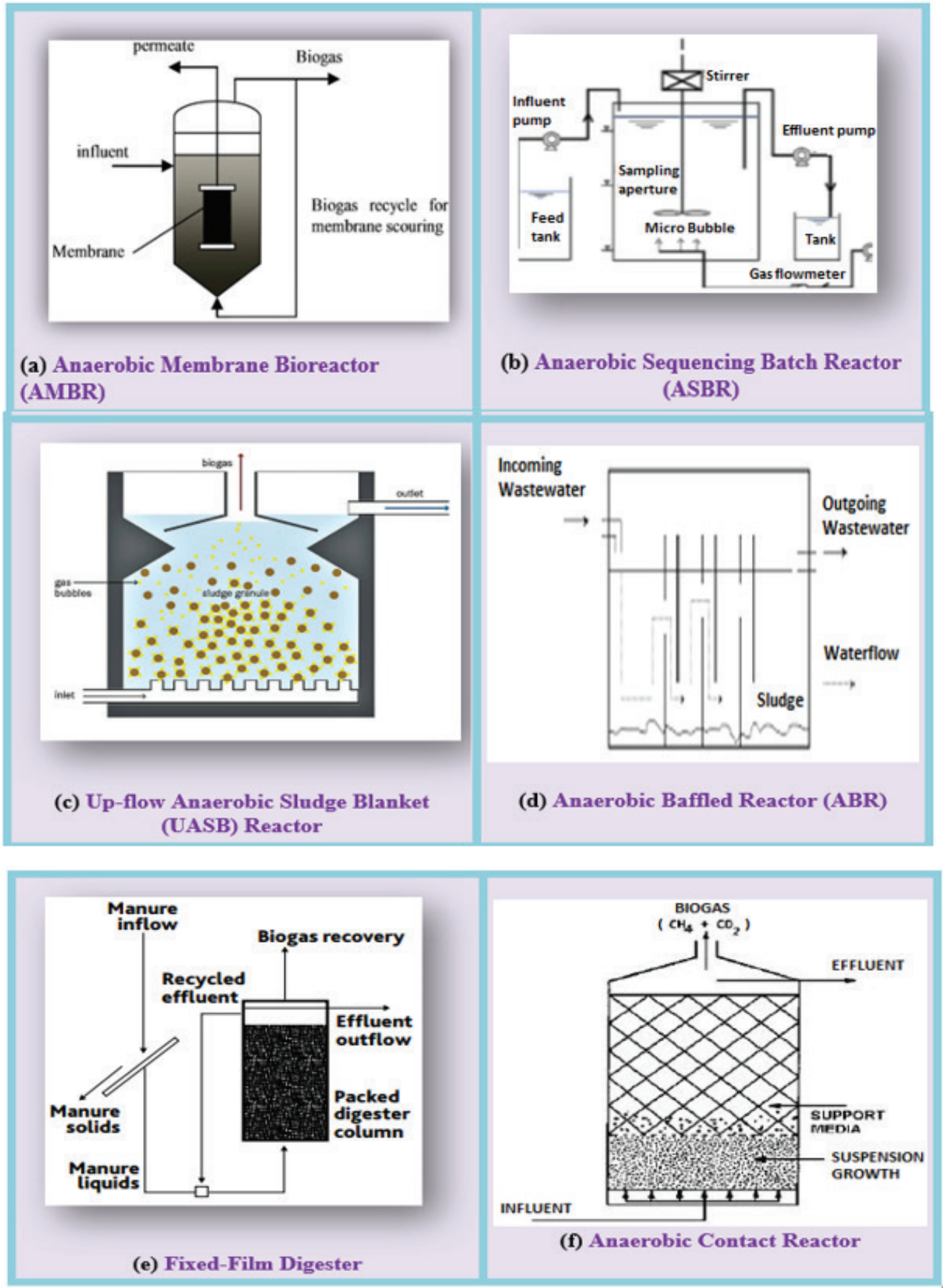

Figure 1. Schematic diagram of notable reactor types [From Chen & Neibling [22], with permission from Stanford.edu]

Table 1. Previous studies on different method of biogas production and treatment of pharmaceutical wastewater

Type of waste treated	Method	Biogas/ methane produced	Material & amount removed	Drawback	References
Pharmaceutical wastewater	Anaerobic bio-entrapped membrane reactor (AnBEMR)	Methane: 142.2±34.4 mL CH_4/ gCOD	5–10% higher TCOD removal efficiency than	Particular waste removed is not stated	[115]
Antibiotic	Thermal hydrolysis pretreatment and Anaerobic Digestion	Biogas: 289.90 mL gVS^{-1} untreated & 27.6% more after pretreatment	Spectinomycin mycelial residues of 265 mg L^{-1}	Serum bottles and not standard reactor types was used	[83]
Pharmaceutical waste fermentation broth	Mesophilic reactor	Methane: 22.5 L d^{-1} in 10 days only	Spent mycelia + Corn-grass silage + Pig slurry	Production of gas forced-stopped by an inhibitor	[49]
Pharmaceutical effluent	Anaerobic fluidized bed reactor	Biogas: 5.62 L/day	91.2 % COD removal	Particular effluent removed is not known	[204]
Antibiotic wastewater	Anaerobic multiphase hybrid reactor (AMHR)	Biogas: 8780 mL/ day	Sewage sludge + cow dung + Wastewater	Wastewater % removed is not mentioned	[191]
Pharmaceutical industrial effluent	Anaerobic Suspended Film Contact Reactor	Methane: 0.29-0.33 m^3 CH_4/ kgCOD	-	Type of effluent is not stated	[186]
Pharmaceutical effluent	Anaerobic batch reactor (bottles)	45-60 mL	Cow dung + Effluent	No effluent type or constituent and not a membrane system used	[58]

(2006)[216] enumerates the type of medical waste generated in Nigeria where they list waste human blood and products of blood, pathological wastes, body parts, and contaminated animal carcasses from autopsy or surgery as the most prevalent.

Medical waste generation in China was foretold to increase far above 50% by 2030 from a current yearly production of around 650,000 tons looking at a growth rate of 19-25%, largely because of huge population [217–220]. During the COVID-19 period, about 2,600 tons of biomedical waste was produced from 24 temporary quarantine facilities and households, 8 residential centers and 91 COVID-19 hospitals in South Korea [221]. New Delhi, the capital of the second most populous nation in the world, India, generates 65 tons of biomedical waste – where elsewhere in the country (Tamil Nadu), the massive nonmedical waste (food leftover, plastics and paper) generated are subject for research in the medical institution (Christian Medical College) in that part of the country, which is generating approximately 11,000 kg/day [212, 222]. In neighboring state within Pakistan, Peshawar, private hospitals produce 79 kg/day of medical waste, government teaching hospitals generates 900 kg/day, and government non-teaching hospitals produce 167 kg/day as reported by Giakoumakis et al. [223]. In Dhaka, Bangladesh, around 200 metric tons of medical waste (about 6% of overall waste) are produced daily – whereas on April 2020, the COVID-19 epidemic results in 14,500 tons of biomedical waste in the whole country [221, 224]. Annually, Malaysia is said to generate up to 33,000 tons of clinical waste [225]. In North America, Brazil, as estimated, 76% of the township dispose municipal and medical waste together in landfills; non-disposable medical devices (e.g., endoscopes) are reused in 41% of Canadian hospitals; and 2.5-3 million tons of biomedical waste is generated annually in the US [221, 226–228]. According to Chisholm et al. [229], Tunisia generates approximately 18,000 tonnes/year presently of medical waste, in addition to 8000 tonnes of hazardous waste. Morocco, Nigeria and majority of other African countries has no such information at the moment [226, 229].

Based on Chisholm et al. [229]'s assertion, approximately, 0.5 kg/bed/day of hazardous waste are produced in high-revenue countries, higher than 0.2 kg/bed/day rate of production in low-revenue countries. And according to Burik [213], a hospital bed has the capacity of generating 0.5 kg of waste per day, far below the rate in various countries as illustrated in Table 2.

Infectious and Sharp Waste

Infectious waste originates from infected patients in quarantine wards and are essentially cultures, contaminated blood, tissues, excreta and transmittable agents or

Table 2. Average daily weight of medical waste generated in hospitals across the world per bed

Country	Total medical waste (kg/bed/day)	Reference	Country	Total medical waste (kg/bed/day)	Reference
Algeria	1-1.72	[229]	Latvia	1.18	[223]
Bangladesh	0.57	[205]	Lebanon	2.45	[223]
Belgium	1.4	[223]	Libya	1.3	[223]
Brazil	4.4	[223]	Malaysia	1.9	[225]
Bolivia	0.5	[223]	Mexico	2-2.2	[221]
Bulgaria	2	[223]	Netherland	1.7	[223]
Canada	8.2	[223]	Nigeria	2.5	[223]
China	0.5-0.8	[230]	Norway	3.9	[223]
Ecuador	0.4	[223]	Pakistan	2-2.2	[223]
Egypt	0.7-1.7	[229]	Palestine	0.33-1.57	[205]
Ethiopia	1.1-6.03	[229]	Portugal	1.5	[223]
France	3.3	[223]	Serbia	1.9	[223]
Germany	3.6	[223]	Spain	4.4	[223]
Greece	1.4.-1.9	[230]	Sudan	0.38-0.87	[229]
India	0.5	[223]	Taiwan	1.9	[223]
Indonesia	2.23	[221]	Tanzania	0.84-5.8	[206]
Iran	3.5-4.42	[206]	Thailand	2.85	[221]
Ireland	5.03	[231]	Turkey	0.63	[230]
Italy	1-2.08	[232]	UK	3.3	[223]
Japan	2.3	[231]	USA	8.4	[223]
Jordan	3.49	[206]	Vietnam	1.57	[223]
Kazakhstan	5.34	[223]	Yemen	2.41	[223]
Kuwait	3.8	[223]			

equipment from laboratory tasks [207, 224, 231-233]. They results in diseases such as tetanus, tuberculosis, diarrhea, whooping cough and pneumonia that are spread by pathogens (e.g., streptococcal infections) due to inappropriate handling and waste management practices [209, 212, 234-235]. To arrest the dangers caused by open defecation, the Nigerian government in 2019, signed an executive order in that respect, as excreta could host harmful pathogens [149]. Most notable outbreak is the COVID-19 virus which affects approximately 75 million people worldwide as well as the Ebola virus [233, 236]. More than 50% of deaths is linked to health-care waste related activities and diseases according to Odumosu [7], surpassing the 1996 WHO number equivalent to almost 50,000 deaths globally [212, 235]. The largest deaths of infected humans were recorded in 2014, where Ebola took the life of 8 people in Nigeria and hundreds more in Africa – preceded by the COVID-19 virus that kills 1.66 million across the globe in 2020 [233, 236]. Due to rapid industrialization, 3.4 million people die annually across the globe from waterborne diseases [48]. To avoid future occurrence of the menace caused by infectious waste, the presence of incinerators, just like the one at Al Shifa hospital (in Gaza Strip-Palestine) is a way of ensuring effective disposal of infectious toxic waste [205].

However, literature documentation of infectious waste generated is scanty, but there has been a report by Hassan & Shareefdeen [233] which puts the amount of infectious clinical waste produced in underdeveloped nations at 0.2 kg/day. This quantity falls short of amount from Quezon City in four specialty hospitals (namely, Philippine Children's Medical Center-PCMC, National Kidney and Transplant Institute-NKTI, Philippine Heart Center-PHC and Lung Center of the Philippines-LCP) with total capacities of 1009 beds and mean infectious waste per day of 579 kg [237]. Sharps are syringes, broken ampoules, surgical aids/instruments, hypodermic needles, needles, scalpels, knives, broken glass infusion sets, blades and glassware [1, 7, 224, 233]. As for sharps, 91 healthcare services in Southern Brazil based on a survey, only care about biomedical sharp waste management without any regards to other medical wastes [216, 238].

Pathological Waste and their AD

What constitutes pathological waste are organs, blood, tissues, human or animal body parts (also called anatomical

waste such as amputated arms or legs and placenta), body fluids, infected animal carcasses, and human fetuses [1, 205, 207, 224, 239-240]. They are products of medical and veterinary hospitals with disease-spreading capabilities, odor pollution and insects and rodents attraction [1, 241]. Presently, based on literature studies, the most used medical waste for biogas production is placenta. Placenta have been digested in Philippines, Tanzania and India to produce biogas. In his studies, Kabbashi et al. (2018)[209] found that the rate of production of waste blood from laboratories is 21.1% and that of expired blood bank is 54.9% in Khartoum hospital, in Sudan. But likened to placenta, blood is least exploited despite being a good feedstock for biogas production.

At Mwananyamala Referral Hospital in Dar es Salaam, Tanzania, a 38.5 m^3 bioreactor produces 800 litres of biogas in a 90 days long digestion of 46 placentas daily feed, weighing 560g each and 1700 litres of gas from food residues in a separate digestion reported by Kellner [242]. From the same hospital, Honest & Saria (2020)[240], found that co-digestion of 83.1±14.7 kg/day of food waste and 25.6±4.5 kg/day of placenta in a 32 m^3 reactor at a pH between 6.3-8.0 and temperature of 30.3°C produces 2.5 m^3/day of biogas after 18 weeks, at a pressure ranging from 5-33 kPa. Also, ten regional referral hospitals, namely, Mbeya, Geita, Dodoma, Ruvuma, Arusha, Iringa, Kigoma, Njombe, Manyara and Mwanza that will make use of food leftovers and placenta in fixed underground round tank to produce biogas, had been targeted by the Tanzanian government, in an attempt to replicate those in Ubungo Municipal Referral Hospital and the Dar es Salaam's Mwananyamala Regional Referral Hospital used for heating and cooking [241]. Moreso, a contract was awarded to MOCUBA Enterprises Company Limited to build a biogas facility at Sinza hospital in Dar es Salaam to produce biogas from placenta and other waste in 2020 [243], as shown in Figure 2.

Jared Escarpe, a Filipino, suggest the construction of biodigester at the Perpetual Succor Hospital, Cebu City in the Philippines for co-digestion of food, garden waste and placenta to generate methane for cooking and powering the hospital. The project was supported by United Nations Development Programme (UNDP) and coordinated by Health Care Without Harm (HCWH) [244]. The District Hospital of Kalikot aims at using pregnant women placenta and degradable waste by building a biogas plant that will yield the needed amount of gas to boil and purify water required by patients in the hospital [245]. In some hospitals, instead of pathological wastes, other non-medical organic waste generated inside the health facility are used to produce biogas. Typically, in 2007, the Newham General Hospital in UK began composting food waste, in accordance with Ignou et al. [227] report. Likewise, the Holy Family Hospital in Bandra, India converts kitchen waste in the facility to biogas (1 cylinder capacity) and biofertilizer using a model created by Kabir Udeshi [246]. First and foremost, unlike food waste, digestion of placenta takes

Figure 2. Biogas plants at two Tanzania hospitals [From Honest & Saria [240] & Kellner [243], with permission from JEP & GHW, respectively].

Table 3. Biogas from biodegradable hospital waste

References	Medical waste	Biogas volume	AD condition
Kellner (2019)[242]	Placenta	800 litres	90 days RT & 38.5 m^3 digester
Honest & Saria, (2020)[240]	Food waste + Placenta	2.5 m^3/day	32 m^3 digester; 6.3-8.0 pH; 30.3°C & 18 weeks RT
Dhakal et al., (2015)[247]	Food leftovers + Amputed pathological waste + Cow dung	5.78 m^3/day	21 m^3 digester
Rahman & Melville (2023)[248]	Hospital waste	62 m^3	500 kg Feed
Kabbashi et al. (2018)[209] & Mohammed et al. (2017)[207]	Red blood cell & Whole blood cell	304-3075 mL CH_4	Different samples and reacting conditions

AD: Anaerobic digestion.

longer fermentation time of around 180 days. Though 1 kg of placenta is equivalent to 31.3 liters of biogas above food sample yield [243]. Limited resources (Table 3) are found in the literature on biogas recovery from medical waste.

BIODEGRADABILITY OF ANTIBIOTICS CONTAMINATED MANURE

Since 1990s, the anaerobic digestion of synthetic drug based effluents and antibiotics had been studied by various researchers using sulphate reducing organisms, iron reducing organisms, methanogenic organisms and nitrate reducing organisms [204, 249]. Before the AD of waste of pharmaceutical origin, their toxicity and biodegradability should be determined in advance for appropriate selection of a suitable operational parameters, as some antibiotics promote AD performance at certain conditions [131, 250-251]. In essence, low drugs concentration positively inhibits biogas yield whereas high drugs concentration stimulates the process [145]. So, it affirms the reason why some antibiotics, PCPs and chemical/pharmaceutical wastewaters are inhibitory, toxic and hard or partially degraded as they affect methanogen's growth and physiology and the efficiency of the process [131, 252, 253]. Typically, carbamazepine, diclofenac and tramadol, based on the SMA, is likely to be stimulating at low concentration while carbamazepine at high concentration – bearing similarity with ciprofloxacin which can either be stimulatory and non-stimulatory at high or low amounts [93, 145]. Such inhibitory properties of antibiotics on methane and biogas synthesis are due to pH reduction, dissolved COD and volatile fatty acids (VFAs) accumulation; such as large accumulation of VFA during AD of 45-50 mg/L of SMX [93, 250].

For example, antibiotics like chloramphenicol, neomycin, tylosin, doxycycline, chlortetracycline and streptomycin caused slight inhibitory effect on CH_4 production while erythromycin concentration of up to 250 mg/L, linear alkylbenzene sulfonate (LAS) and carbamazepine (CBZ) did not inhibit biogas generation according to literature [111, 142, 249]. Similarly, amoxicillin (60 mg/L) reduces the cumulative biogas and CH_4 production by 25%; tetracycline and sulfamethoxazole mixture (0.5–15 mg/L) and penicillin inhibits AD by 25% and 35% respectively in an ASBR; chlortetracycline reduces CH_4 production by 20% when fed to pig and; oxytetracycline strongly inhibits AD completely, except at concentrations around 250 mg/L in some cases [90, 102, 110, 141, 249]. On the other hand, Azizan et al. (2021)[141] found that an 8.5 mg/L concentration of tetracycline in pharmaceutical effluents totally inhibit CH_4 production. Stergar & Konèan [251] states that, equipment selection for anaerobic treatment of certain waste depends on the nature of the substrate and the process limiting steps. Sulfamerazine in pharmaceutical wastewater, as an example was found to be biodegradable and only inhibit methanogenesis at threshold concentration of 90 mg/L in a UASB bioreactor as reported by Li et al. [111]. Also, heavy metals and pharmaceuticals removal from pharmaceutical effluent sludge using steam explosion pretreatment method was found to improve its biodegradability and biogas yield (up to 380 mL CH_4/gVS) when pretreated at 10 bar for 15 minutes [254].

The AD technology offers reliability in treating animal manure, tannery waste, textile, distillery, personal care products (PCP) and both low- and high-strength pharmaceutical industry wastes, as it needs low energy compared to aerobic process which offers a decrease in biomass yield [186, 189, 255–257]. To address the disparity, Iliopoulous et al. [156] explored the joint use of anaerobic MBBR and aerobic MBR for pharmaceuticals removal and municipal wastewater treatment. PCPs such as diclofenac and contraceptives in soils are non-biodegradable and affect live organisms in the ecosystem (the case of reproductive failure in fish caused by 17-α ethinylestradiol) [72, 78, 92, 258-259]. According to Omil, et al. (2007)[258] reports, AD of PCPs have earlier been studied in sewage sludge. Even though antibiotics in animal waste pose significant side effects during their digestion, AD remains the most efficient way of treating antibiotic-contaminated livestock wastes [250]. Antibiotics (e.g., ampicillin, oxytetracycline, tylosin, chlortetracycline, florfenicol and sulfamethazine) are often spotted in cow and pig manure [85, 102, 250]. Oxytetracycline and chlortetracycline in pig manure, for instance, decreases

CH_4 production during AD by 56-62% while at mesophilic conditions, oxytetracycline in cow manure reduces biogas production by 60% [250]. Gaballah et al. [260] mentioned that the veterinary antibiotics present sometimes in mixed form in manures, can be removed before its AD. Nesse et al. [261] reported that the edible mushroom grown on PPR-polluted biogas digestate led to the uptake of the pharmaceuticals present in it in low amounts.

Medical and Pharmaceutical Sludge Digestion

Literature studies shows that pretreated medical cotton industry wastes, after 90 days fermentation yields 26.916 mL/gVS and 51.622 mL/gVS of biogas at respective mesophilic and thermophilic temperature regimes [262]. Biogas plants in the past 10 years have been constructed near healthcare facilities in Madagascar, Nepal and Tanzania by the Health, Environment and Climate Action Foundation of Nepal and the HCWH [263]. Based on digestion carried out by Dhakal et al. [247] for 147 days in Bir Hospital (established in 1889), Kathmandu using a 21m^3 digester, 95 kg/day of mixed healthcare waste produced 5.78 m^3/day of biogas. In an experiment carried out by Mohammed et al. [207] and Kabbashi et al. [209], three Red Blood Cells (RBCs) samples (A: 446.4g RBC with TS = 22.4% operated at 31.57°C for 150 days produces 1470 mL of methane gas, B: 348.4g RBC with TS=28.7% operated at 29.44°C for 110 days produces 2625 mL of methane gas, and C: 348.4g RBC with TS=28.7% operated at 29.25°C for 90 days produces 304 mL of methane gas) and two whole blood samples (D: 274g RBC with TS=36.5% operated at 29.25°C for 20 days produces 3075 mL of methane gas and E: 274g RBC with TS=36.5% operated at 29.89°C for 20 days produces 2570 mL of methane gas) were used at Khartoum, National

Figure 3. Biogas plants for ad of medical and pharmaceutical waste/effluents [From Stringer, Avadhani & Rege; i.e., [263, 266-267], with permission from GPP, Embio Ltd. & IBA].

Centre for Energy Research (NCER) to assess the methane gas yields of biomedical wastes. Dextran pharmaceutical effluent released from Xinlun Pharmaceutical Factory in Jianyang City, China yields 215.85 L/kgCOD of biogas after 28 days in a 635.5 liters of plexiglass digester according to Xu et al. [30]'s findings. Huang et al. carried out AD of 3 kg of dextran contained in activated sludge at 21-33°C for 42 days yielding 201.77 litres (13.31 L/kgCOD) of biogas when there was no mixing and 381.60-455.05 litres (19.81-21.07 L/kgCOD) when mixing was involved in a 750 liters biodigester. Findings of Gustavsson et al. [264] shows that 180 mL/gVS of CH_4 is produced by digesting industrial sludge from Björkborn industrial area in Karlskoga polluted with explosives, nitroaromatic compounds and pharmaceutical residue – whereas co-digestion of the same sludge with oat gives 270 mL/gVS of CH_4. Meanwhile, Yin et al. [164] produced 499.46 mL/gTS of biogas from pharmaceutical sludge at 10.32 inoculum-to-substrate ratio. Adesina & Felix [98] reported that diclofenac was biodegraded only at sludge retention time of 8 days minimum. There was 20.8% improvements in CH_4 generated when anaerobic granular sludge and anaerobic suspended sludge was digested with 1000 mg/L LCM. Biogas yield and CH_4 content during norfloxacin and tetracycline distillery wastewater purifications are 191 cm^3/g and 254 cm^3/g and 70% and 67% respectively [87]. Currently, addition of zero valent iron (ZVI) and granular activated carbon (GAV) to improve AD of pharmaceutical wastewater had been studied [265]. Practical applications of medical and pharmaceutical digesters for biogas production are shown in Figure 3.

Embio Limited, India, converts molasses into drugs intermediate by fermentation which in turn generates substantial amount of waste with biogas potential. Thus, a fixed film digester anaerobically digest the 300 m^3/day of wastewater generated at 50-55°C (& pH=7.2), and yields 14500-15000 m^3/day of biogas which is rerouted to boilers through gas blowers to generate steam for reuse [266]. Also in Figure 1c, Anthem Biosciences Private Limited treats thick slurry fermentation waste broth (pharmaceutical effluent) from tetrose, peptone, soya flour and cultures as raw material to produce 2250-2500 m^3/day of biogas [267].

Biogas from Herbal Pharmaceutical Waste

India has witnessed rapid growth and development in the manufacture and use of herbal pharmaceutical products to treat diseases, while in Poland, the country is regarded as a major herbs producer in Europe between 2012- [192, 268]. Agricultural outputs such as herbs has also been used to formulate pharmaceutical products some of which (real herbs or herbal industry wastes and effluents) can be used to produce biogas and bio-slurry, as they are characterized by high organic content [269, 270]. *Justicia schimperiana* (JS), lemon balm and alder buckthorn are typical examples of herbs or herbal industry waste that has been used as biogas substrates as well as medicinal plants like *Glycyrrhiza glabra* (GG), Mentha, *Cuminum cyminum* (CC), Lavender and Arctium [268, 271-272]. Some of these pharmaceutical herbs are characterized with unpleasant smell and high composition of organic pollutants [192, 272]. GG and CC of 10% TS, produces 13471 mL and 13611 mL of biogas after digesting 250g each of the plants in batch reactors at 35°C, according to results obtained by Fardad et al. [271]. Findings from experiment conducted by Czubaszek (2019) [268], shows that alder buckthorn and lemon balm produces 386±33 and 461±23 NL $kgVS^{-1}$ of biogas within a 35 days retention period. Patel et al. [273] stated that the biogas potential of herbs is naturally favoured by their high organic matter content. Also, from the Laboratory of Ecotechnologies (the biggest biogas lab in Poland), biogas produced is 172.18 m^3/Mg FM (or 526.23 m^3/Mg TS) at pH of 5.4, from a herb of 32.70%TS and 90.13 %VS [274]. Peni et al. [41] recorded 169.4 NL/kgVS and 193.2 NL/kgVS of biomethane from the perennial plant called *Helianthus salicifolius* – from raw biomass and silage respectively.

Human Urine Digestion

Between 70-90% of antibiotics are usually released in their original form via urine and feces [275]. Human urine with pH ranging from 4.8-7.5 contains 99.6% water and 0.4% dry matter, in addition to 2% w/w urea that is readily hydrolyzed to CO_2 and NH_3 [21, 276]. According to Kim et al. (2020)[276], an average human produce 1.4 liters of urine that contributes 50% of phosphorus and 85% of nitrogen in domestic sewage. Accordingly, Haque & Haque [21] shows that mineral nitrogen fertilizer in Sweden have similar effect on plant growth compared to human urine. Mono- and co-digestion of urine with other substrate have also been studied by researchers. For instance, the ratio, "cow dung : human urine : water" (50:10:40) generates 43.42 litres of biogas while 1:1 ratio of human urine and cow dung produces 41.95 liters of biogas at 28-35°C [21]. In another studies, the addition of 250 mL urine to 100 g of boiled rice produced maximum CH_4 and biogas [277]. A practical approach towards generating electricity and cooking gas from biogas plants to be constructed by Lumos Laboratories Nigeria Limited was made by the Federal Government recently, which would be adopted at prisons across the state. The plants would use human urine at correctional centers in the country and was pioneered by Nwosu (Patent No. NG/P/20/2013/699) in 2014 [278].

Kinetics and Optimization of Biogas Production

In the literature, kinetics of biogas production from medical and pharmaceutical wastes is scanty. This study identifies the Monod, Haldane, Andrew, Modified Gompertz, modified Stover-Kincannon and Van der Meer and Heertjes kinetic models as some of the mathematical models for optimizing AD and biogas production associated with pharmaceutical wastewater as feedstock [191, 279–281]. The Andrews' kinetic model is a concentration-dependent process designed to biologically eliminate and reuse liquid toxic waste. The model is best suited for

pharmaceutical waste/wastewater digestion at low substrate concentration, because at high concentrations, toxicity and inhibitory effects are seriously felt [53]. In numerous occasions, there is no proportionate relationship between the inhibitory effect and the inhibitor concentration on the kinetics, hence a non-linear function (modified propionate and acetate consumption model) to study the inhibition of pharmaceuticals on both acetogenesis and methanogenesis can be used [70]. Amin et al. [90] examined the effect of high OTC loadings on acidogens and methanogens using Haldane inhibition kinetics, where they realized that an increase in toxicity at increasing loading rate signifies a decrease of the Haldane inhibition constant. Though the Monod equation does not explain possible inhibitions in AD systems involving pharmaceutical effluents, the model can be applied while studying the kinetics of biogas production using biodegradable pathological waste. Equation 1, 2, 3 and 4 are the Monod, Andrews', the propionate and acetate consumption rate and Haldane kinetic models [53, 70, 90]:

$$\mu = \mu_{max} \frac{S}{K_s+S} \quad (1)$$

$$\mu = \mu_{max} \frac{S}{K_s+S+\frac{S^2}{K_I}} \quad (2)$$

$$r_{modified} = r. \frac{1}{1+\left(\frac{I}{K_I}\right)^m} \quad (3)$$

$$\mu = \frac{\mu_{max}\, S}{(K_s+S)\left(1+\frac{S}{K_I}\right)} \quad (4)$$

where, μ = specific growth rate of biomass (/day), μ_{max} = maximum specific growth rate of biomass (/day), S = biodegradable pollutant (substrate) concentration (mg/L), K_S = half saturation coefficient (mg/L), K_I = inhibition coefficient (mg/L), $r_{modified}$ = propionate or acetates consumption rate, I = concentration of the pharmaceutical and m = constant representing the non-linear dependence of inhibition (when m = 1, the inhibition reduces to non-competitive type; when m < 1, inhibitory effect on the kinetics tends to be insensitive with inhibitor concentration and; when m > 1, inhibitory effect on the kinetics tends to be very sensitive with inhibitor concentration). Human and animal urine from patients at medical centres are typical example of biogas substrates containing inhibitors since they are released unchanged from the sick organism consuming pharmaceuticals. Optimization of biogas production from urine can be carried out using Equations 2 and 3 if the patient animal is known to consume antibiotics and other inhibitory drugs. Nevertheless, such studies is still lacking, kinetics of biogas production using non-contaminated urine has been analyzed by Sau et al. (2013)[277] using the Chen and Hashimoto model.

WASTE MANAGEMENT PRACTICE

In this work, three types of waste have been identified, namely, chemical, medical and pharmaceutical wastes. Before the detection of pharmaceuticals in the aquatic environment, they have been detected on land and studied since the 1970s [66]. In water bodies, many are described as pseudo-persistent, i.e., relatively having short half-lives in the ecosystem with notable effect to humans such as reproductive damage, cell inhibition and behavioral changes [92, 98]. However, they are unlikely to cause significant harm on land (waste of hospital, landfill, agricultural, graveyards and industrial pharmaceutical activities), because they occur at very low concentrations; based on few research conducted to ascertain their toxicity to the ecosystem [75, 92, 131]. Pharmaceutical waste are simply contaminated, prescribed, expired, spilt, vaccines, sera, and propriety drugs and unused pharmaceutical products which is no longer needed and so is disposed off [139, 207, 282]. Unused medications could cost billions of dollars globally, and according to a US report, more than 50% of patients stores unused and expired drugs in their homes which they end-up flushing down the toilet [98, 283]. While studying 427 households in Nigeria, Auta et al. [283] found that 94.1% of households keep unused medicines either for re-use or serve another sick household member with 'probably' a similar medical issue But elsewhere (Lagos), out of 376 healthcare workers, 40.4% returned unused drugs, 41.2% returned expired ones to manufacturers and 19.9% return it to sellers according to a survey carried out by Adesina & Felix [98]. Reasons resulting in unused drugs are change in treatment plan, recommended drug is inappropriate for the need, non-adherence to therapy, medications reaching expiry dates, supply of unwanted quantities, adverse drug event, over prescribing, and nonrecognition of drugs due to a foreign label [283, 284]. In Lagos, Nigeria, absence of proper disposal guidelines for unused medication according to global best practices and a non-return policy (which is only 22.9% according to a US report but a predominant practice in Sweden) are challenges to address [98, 285].

Individuals and households, as a common practice, dispose medicines in garbage; especially in countries like Lithuania, United Kingdom and Kuwait [285]. A study of a pharmacy in Kuwait shows 73% of the respondents use trash to dispose unwanted medicines, 38.6% of doctors in South India dispose pharmaceuticals in dustbin and 24.6% flush them down the sink, a method commonly practiced in the US, and 59.7% of the 22 wards studied in Maiduguri, North-Eastern Nigeria dispose expired drugs using household garbage [98, 285]. Unprofessional disposal of expired pharmaceuticals (e.g., landfill and water bodies) had previously resulted in deaths and medication poisoning in scavengers, children and adult, whereas those emptied into

sewage systems kills bacteria responsible for its treatment [140, 284]. For example, waste drugs could be stolen from storage and sidetracked to the market for misuse and resale [284]. In Nigeria, non-prescribed drugs such as antihypertensives, analgesics, antimalarials, antibiotics, steroids, antacids, anticonvulsants, and antihistamines are highly consumed [66].

Management of chemical and biomedical waste is also a thing of concern. Chemical waste materials entails hormones, antioxidants, plasticizers, detergents, insecticides, pesticides, fire retardants, disinfectants, human and veterinary drugs that originates from homes, agricultural applications, dental, medical, veterinary laboratories and industries [7, 38, 89]. Biomedical waste as explained earlier, emanates as a result of diagnosis, immunization or treatment in medical or research facilities which are categorized into bio-hazardous and non-hazardous waste with characteristic high BOD content (about 234 ppm in Nigerian hospital sewage) [226, 286, 287]. For instance, about 26.5% of waste produced in 5 healthcare institutions in Nigeria's capital territory is hazardous medical waste based on a 2006 study [214]. Fundamental data regarding medical waste disposal emerging from hospitals is not available in Nigeria and the responsibility for its disposal is not assigned to anyone nor is it clearly defined [236, 283]. Except for Lagos in Nigeria, that at least constructed several highly-equipped transfer loading stations at strategic locations in the state [288], as shown in Figure 4.

Previously, moves have been made by the American Hospital Association (AHA) and the Environmental Protection Agency (EPA) in 1998 to reduce health care waste volume from 2005-2010, and in 1980 in Malaysia, clinical waste management began in the country [225, 286]. As a solution to menace posed by medical and pharmaceutical waste, Nyaga et al. [289] suggests the lessening of pharmaceutical waste generation, its collection at designated sites (e.g., Figure 2), implementation of a take-back options, application of recent technology and the lunching of public awareness campaigns together with policies and guidelines for a safe disposal. But in developing African countries, especially Nigeria, only few are well informed about the dangers posed by medical waste to the environment – specifically, in Tripoli, Libya, out of 300 medical waste handlers surveyed, only 7% had received training vis-à-vis its handling [228, 239]. In addition, zero training was given to medical waste personnel in Serbia while only 23% received such training in Bangladesh [228]. But surprisingly, in North-Eastern Nigeria, and based on Okoro & Peter [285]'s survey, more than 80% of the people knew the impacts of improper discarding of medicines to public well-being. Currently, a company based in Amsterdam (Pharmafilter), has developed a technology that digest biodegradable hospital waste anaerobically, thereby combating antibiotic resistance and in turn uses the biogas generated to power itself, as shown in Figure 5.

The use of the Pharmafilter technology would however be based on the time bound planning (scheduling) of various waste management steps of segregation, collection, storage, treatment to disposal [1, 229]. It is worthy of note that segregation is best practiced at place of waste

Figure 4. Special containers for loading medical waste at a transfer loading station in Lagos, Nigeria [From Awodele et al. [288], with permission from BMC Public Health].

Figure 5. Anaerobic digestion of hospital waste in Amsterdam, Netherland. [From Burik [213], with permission from LABIOTECH].

generation (usually the medical arena) by physicians, technicians and nurses [227]. In Africa, Indonesia and Korea, mixed waste containing hospital and municipal waste are commonly found in waste streams, bins, residential waste landfills and road sides [228, 288]. At present, Nigeria has no planned time scheduled healthcare waste management system and only 16.9% of health facility waste had been reported to be segregated in Lagos [229, 236]. Furthermore, syringes and other medical waste are regular contaminants of beaches of Bali in Indonesia [228]. Figure 6 shows medical waste being separated from non-medical waste at a hospital at Tamil Nadu, India.

Waste management practices for medical, pharmaceutical wastes and pharmaceutical process wastewater are inertization, deep burial, waste immobilization, microwaving, encapsulation, secure land filling, burning and incineration [98, 240, 290]. Honkanen [291] carried out a feasibility assessment on incenerating medical waste in South-Asia.

Figure 6. Segregation of medical from nonmedical waste at Christian Medical College, Vellore, Tamil Nadu, India [From Thomas et al. [153], with permission from IJERT]

Incineration is a high temperature (600-1200°C) thermal process that combust waste to gases and inert materials [7, 238]. Controlled air, rotary kiln and excess air incinerators are the three main kinds of incinerators [208]. Novel incinerator technologies are foundries or coal-fired thermal power stations and cement kilns (suited for expired pharmaceuticals) that disperse unwanted gases through tall chimneys [208, 284]. Sometimes these incinerators are made of bricks, especially the De Monfort incinerators [292]. Open burning at low temperatures and incineration release carcinogenic toxic chemical products called furans and dioxins that pollutes the air, thereby causing respiratory illnesses and cancer, as well as residual ashes [7, 209, 212, 284]. Apart from residual ashes, dioxins and furans, incinerators are sometimes left with needles, blades, heavy metals, polycyclic aromatic hydrocarbons (PAHs) and other sharps [3, 209, 238]. China has the highest dioxin emission threshold (5 ng/m^3) than the majority of European nations [209].

Nevertheless, incineration remains the most extensively used technique of treating hospital waste in numerous places around the world [7]. In Africa, Ethiopia, Botswana, Algeria and South Africa use incinerators: Tanzania in recent past constructed 13 pilot small scale incinerators [216]; in Ibadan, Nigeria, only few hospitals use incinerators [226]; and inadequate incineration practices in Tunisia is responsible for 90% of dioxins and furan emissions [229]. Six out of nine private healthcare facilities in Iran having incinerators, face mild operational problems; Korea is witnessing an insufficient controlled practices; incinerators in Malaysia are meant for hazardous and infectious waste treatment and; 67% of hospitals incinerate their infectious waste in the US [225, 226, 228, 288]. Hitherto, it took Eritrea 6 months to burn 7 truckloads of expired aspirin tablets; the act of burning unused and expired medicines at home is commonly practiced in Lithuania; while in Ibadan, Nigeria, approximately 30% of hospitals apply the open burning process [226, 284, 285].

CONCLUSION

Influence of wastes from pharmaceutical industries and medical health centers on the environment is a thing of concern to safeguard the habitat. Researchers are currently looking at ways to dispose or decompose these wastes and their effluents by transforming them to bioenergy or biofuel source by harnessing their unique characteristics. The market for pharmaceutical industry is growing and has witnessed skyrocketed increase in drug mass production due to recorded spread of infectious diseases occasioned by the famous Ebola and COVID-19 virus worldwide. This has also added to the amount of waste emerging from hospitals globally. Though not all these wastes are biodegradable due to their inhibitory or toxic nature, researchers and environmental management experts are constantly trying their luck to produce biogas from both pharmaceutical and medical waste, and had attempted to build biogas plant at close proximity to hospitals in some countries. However, incineration and open-burning remains the most applied waste management practice at the moment with attendant harmful effect to humans.

Construction of biogas plants is therefore encouraged to digest biodegradable pharmaceutical wastewater and medical waste, because it is safer than the combustion processes. Findings show that degradation of pharmaceutically contaminated effluents produces less biogas and requires longer retention times of more than 100 days due to the presence of negligible biodegradable matter or inhibitors. In Sudan, 1470-3075 mL of methane has been obtained from blood biodigestion. Around 2.5m^3 of biogas has been obtained by degrading placenta at Mwananyamala hospital in Tanzania and 5.78m^3/day of biogas has been obtained through the decomposition of pathological waste near Bir Hospital, Nepal. Existing gaps that need to be filled is the practical and purposeful construction of a multipurpose bioreactors (either conventional or nonconventional/membrane reactors) for large scale treatment of pharmaceutical, medical and associated effluent with a biogas and biofertilizer recovery system. Extensive review of literature has shown that such practices are often done at laboratory scale using nonconventional reactors with just few efforts made to recover the potential bioenergy inherent in the wastes. Separation technologies such as liquid-liquid extraction and distillation is recommended where the end-product of the wastewater treatment setup is to produce drinkable water. To sum it up, a biogas or bioenergy recovery system from pharmaceutical, herbal and medical waste has the potential to address environmental pollution, energy security, efficiency, health of (would be affected) humans and animals and unemployment challenges. Chemical or biochemical engineers and biotechnologist should therefore study the kinetics inhibiting anaerobic digestion of some pharmaceutical wastes/effluent in order to discover ways to optimize useful product recovery or suppress their effect during treatment.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. These data are cited accordingly and can found amongst the list of bibliographies used.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Khobragade DS. Health care waste: Avoiding hazards to living and non living environment by efficient management. Fortune J Health Sci 2019;2:14-29. [CrossRef]

[2] Khaire KC, Maibam PD, Thakur A, Goyal A. Biomedical and pharmaceutical applications of xylan and its derivatives. In: Brienzo M, editor. Hemicellulose Biorefinery: A Sustainable Solution for Value Addition to Bio-Based Products and Bioenergy. Singapore: Springer; 2022. p. 447-465. [CrossRef]

[3] Odumosu BT. Biomedical waste: Its effects and safe disposal. In: Chandra R, editor. Environmental Waste Management. Florida: CRC Press; 2016. p. 81-93.

[4] Grabic R, Ivanová L, Kodešová R, Grabicová K, Vojs Staňová A, Imreová Z, et al. Desorption of pharmaceuticals and illicit drugs from different stabilized sludge types across pH. Water Res 2022;220:118651. [CrossRef]

[5] Farissi S, Ramesh S, Muthuchamy M, Muthukumar A. Biodegradation and photocatalysis of pharmaceuticals in wastewater. In: Shah MP, Rodriguez-Couto S, Kapoor RT, editors. Innovative Microbe-Based Applications for Removal of Chemicals and Metals in Wastewater Treatment Plants. Amsterdam, Netherlands: Elsevier; 2022. p. 69-97. [CrossRef]

[6] Golovko O, Ahrens L, Schelin J, Sörengård M, Bergstrand KJ, Asp H, et al. Organic micropollutants, heavy metals and pathogens in anaerobic digestate based on food waste. J Environ Manage 2022;313:114997. [CrossRef]

[7] Golovko O, Kaczmarek M, Asp H, Bergstrand KJ, Ahrens L, Hultberg M. Uptake of perfluoroalkyl substances, pharmaceuticals, and parabens by oyster mushrooms (Pleurotus ostreatus) and exposure risk in human consumption. Chemosphere 2022;291:132898. [CrossRef]

[8] Sharma N, Sharma S. A review on various treatment methods for treating pharmaceutical wastewater. Int Res J Eng Technol 2020;7:1406–1410.

[9] Ahmad S, Abbasi BK, Nazir MS, Abdullah MA. Metal organic frameworks (MOFs) as formidable candidate for pharmaceutical wastewater treatment. In: Lichtfouse E, Muthu SS, Khadir A, editors. Inorganic-Organic Composites for Water and Wastewater Treatment. Singapore: Springer; 2022. p. 37-63. [CrossRef]

[10] Gandhirajan M, Amarnath G, Kavitha P, Bhagavath R. Characterisation and treatment of pharmaceutical R&D wastewater. J Ind Pollut Control 2008;24:1-8.

[11] Mukesha P, Srinivasamurthyb S, Vigneshkumarb PS, Balamurugana P. A treatment of toxic substance in pharmaceutical industry wastewater: A review. Inform Technol Ind 2021;9:410-417. [CrossRef]

[12] Ismail ZZ, Habeeb AA. Pharmaceutical wastewater treatment associated with renewable energy generation in microbial fuel cell based on mobilized electroactive biofilm on zeolite bearer. J Eng 2015;21:35-44. [CrossRef]

[13] Asplund K. Removal of pharmaceutical compounds by anaerobic digestion of sewage sludge. Dissertation. Florida: NOVA Univ; 2022.

[14] Moghaddam A, Khayatan D, Barzegar EF, Ranjbar R, Yazdanian M, Tahmasebi E, et al. Biodegradation of pharmaceutical compounds in industrial wastewater using biological treatment: A comprehensive overview. Int J Environ Sci Technol 2023;20:5659-5696. [CrossRef]

[15] Khodja M, Debih H, Lebtahi H, Amish MB. New HTHP fluid loss control agent for oil-based drilling fluid from pharmaceutical waste. Clean Eng Technol 2022;8:100476. [CrossRef]

[16] Chelliapan S, Sallis PJ. Application of anaerobic biotechnology for pharmaceutical wastewater treatment. Environ Manage Sustain Dev 2011;2:13-21.

[17] Zhong W, Li G, Gao Y, Li Z, Geng X, Li Y, et al. Enhanced biogas production from penicillin bacterial residue by thermal-alkaline pretreatment. Biotechnol Biotechnol Equip 2016;29:522-529. [CrossRef]

[18] Renita AA, Kumar PS, Srinivas S, Priyadharshini S, Karthika M. A review on analytical methods and treatment techniques of pharmaceutical wastewater. Desalin Water Treat 2017;87:160-178. [CrossRef]

[19] Zhao X, Chen H, Zheng Q, Liu J, Pan P, Xu G, et al. Thermo-economic analysis of a novel hydrogen production system using medical waste and biogas with zero carbon emission. Energy 2023;265:126333. [CrossRef]

[20] Gunnerson CG, Stuckey DC. Anaerobic digestion: Principles and practices for biogas systems. 49th ed. World Bank; 1986.

[21] Haque MS, Haque MN. Studies on the effect of urine on biogas production. Bangladesh J Sci Ind Res.2006;41:23-32. [CrossRef]

[22] Chen L, Neibling H. Anaerobic digestion basics. Available at: http://large.stanford.edu/courses/2017/ph240/huang1/docs/cis-1215.pdf. Accessed on Jul 2, 2024.

[23] Ertekin E. Effect of oxytetracycline on biogas production and microbial communities during anaerobic digestion of cow manure by fluorescence in situ hybridization and real time polymerase chain reaction. Master's Thesis. İstanbul: Boğaziçi Univ; 2011.
[24] Korbag I, Omer SMS, Boghazala H, Abusasiyah MAA. Recent advances of biogas production and future perspective. In: Abomohra AEF, Elsayed M, Qin Z, Ji H, Liu Z, editors. Biogas-Recent Advances and Integrated Approaches. IntechOpen; 2021. p. 1-41. [CrossRef]
[25] Luostarinen S, Normak A, Edström M. Overview of biogas technology. Available at: https://www.build-a-biogas-plant.com/PDF/baltic_manure_biogas_final_total.pdf. Accessed on Jul 2, 2024.
[26] Mingchai C, Sangmane P. Decision process for adoption of biogas technology for the sustainable development in Uttaradit Province, Thailand. World Appl Sci J 2012;19:699-703.
[27] Raja IA, Wazir S. Biogas production: The fundamental processes. Univers J Eng Sci 2017;5:29-37. [CrossRef]
[28] Godhole A, Wadetwar RN, Lawal TO, Mahady GB, Raut NA. Microbiology of waste treatment. In: Raut NA, Kokare D, Bhanvase BA, Randive KR, Dhoble SJ, editor. 360-Degree Waste Management: Fundamentals, Agricultural and Domestic Waste, and Remediation. 1st ed. Amsterdam, Netherlands: Elsevier; 2023. p. 185-211. [CrossRef]
[29] Huang R, Mei Z, Long Y, Xiong X, Wang J, Guo T, et al. Impact of optimized flow pattern on pollutant removal and biogas production rate using wastewater anaerobic fermentation. Bioresources 2015;10:4826-4842. [CrossRef]
[30] Xu L, Yang L, Guo S, Zhou J, Luo T, Ran Y, et al. Experimental and CFD simulation study on anaerobic digestion using dextran pharmaceutical wastewater based on cyclic fluidization hydraulic mixing. Environ Prog Sustain Energy 2021;40:13656. [CrossRef]
[31] Fakhri H, Arabaci DN, Ovez S, Aydin S. *Eichhornia crassipes* root biomass to reduce antibiotic resistance dissemination and enhance biogas production of anaerobic membrane bioreactor. Environ Technol 2022;43:4168–4179. [CrossRef]
[32] Kovacs ED, Kovacs MH. Gas chromatographic: Mass spectrometric mining the volatilomes associated to Rhizobiota exposed to commonly used pharmaceuticals. In: Mendes KF, de Sousa RN, Mielke KC, editors. Biodegradation Technology of Organic and Inorganic Pollutants. IntechOpen; 2022.
[33] Díaz AH. Degradation of pharmaceutical compounds by microalgae: Photobioreactor wastewater treatment, biomass harvesting and methanization. Available at: https://www.tdx.cat/handle/10803/390962#page=1. Accessed on Jul 2, 2024.
[34] Goswami RK, Agrawal K, Verma P. An exploration of natural synergy using microalgae for the remediation of pharmaceuticals and xenobiotics in wastewater. Algal Res 2022;64:102703. [CrossRef]
[35] Hassan S, Meenatchi R, Pachillu K, Bansal S, Brindangnanam P, Arockiaraj J, et al. Identification and characterization of the novel bioactive compounds from microalgae and cyanobacteria for pharmaceutical and nutraceutical applications. J Basic Microbiol 2022;62:999–1029. [CrossRef]
[36] Chandel N, Ahuja V, Gurav R, Kumar V, Tyagi VK, Pugazhendhi A, et al. Progress in microalgal mediated bioremediation systems for the removal of antibiotics and pharmaceuticals from wastewater. Sci Total Environ 2022;825:153895. [CrossRef]
[37] Shashikant M, Bains A, Chawla P, Fogarasi M, Fogarasi S. The current status, bioactivity, food, and pharmaceutical approaches of *Calocybe indica*: A review. Antioxidants (Basel) 2022;11:1145. [CrossRef]
[38] Dalecka B. Wastewater treatment from pharmaceutical substances with filamentous fungi. Doctoral Thesis. Riga: Riga Technical Univ; 2021.
[39] Global Methane Initiative (GMI). The agricultural biogas plants in Poland. Available at: https://www.globalmethane.org/documents/Poland-Ag-Biogas-Plants-April-2014.pdf. Accessed on Jul 3, 2024.
[40] Rahmatzafran A, Rossle D, Rianawati E, Loeksmanto IH, Hilbert J, Alemmu S, et al. Biogas markets and frameworks in Argentina, Ethiopia, Ghana, Indonesia, and South Africa. Available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d1e4e65c&appId=PPGMS. Accessed on Jul 2, 2024.
[41] Peni D, Marcin D, Stolarski MJ. Helianthus salicifolius as a new biomass source for biogas production. Energies 2022;15:2921. [CrossRef]
[42] Hasan G, Roubík H, Mazancova J, Banout J. Biogas energy potential in Syria: Prospects and challenges. Prague: Czech University of Life Sciences; 2016.
[43] Ergür HS, Okumus F. Cost and potential analysis of biogas in Eskisehir. Uludag Univ J Fac Eng 2010;15:155-160.
[44] van der Ann L, Reichel A. Bio-waste in Europe-turning challenges into opportunities. Available at: https://cdn.revolutionise.com.au/cups/bioenergy/files/rviur0yxx2psmjoi.pdf. Accessed on Jul 2, 2024.
[45] Gustafsson N. Biogas production based on park waste-Does Helsingborg have the potential? Master's theisis. Lund: Lund Univ; 2019.
[46] Gittelson P, Diamond D, Henning L, Payan M, Utesch L, Utesch N. et al. The false promises of biogas: Why biogas is an environmental justice issue. Environ Justice 2021;1-10. [CrossRef]
[47] Aydin S, Ince B, Cetecioglu Z, Ozbayram EG, Shahi A, Okay O, et al. Performance of anaerobic

sequencing batch reactor in the treatment of pharmaceutical wastewater containing erythromycin and sulfamethoxazole mixture. Water Sci Technol 2014;70:1625–1632. [CrossRef]

[48] Rana RS, Singh P, Kandari V, Singh R, Dobhal R, Gupta S. A review on characterization and bioremediation of pharmaceutical industries' wastewater: An Indian perspective. Appl Water Sci 2017;7:1-12. [CrossRef]

[49] Zupanèiè GD, Gotvajn AG. Anaerobic treatment of pharmaceutical waste fermentation broth. Chem Biomol Eng 2009;23:485-492.

[50] Chelliapan S, Wilby T, Sallis PJ. Performance of an up-flow anaerobic stage reactor (UASR) in the treatment of pharmaceutical wastewater containing macrolide antibiotics. Water Res 2006;40:507–516. [CrossRef]

[51] Gupta SK, Gupta SK, Hung YT. Treatment of pharmaceutical wastes. 2nd ed. Florida: CRC Press; 2004. p. 63-129. [CrossRef]

[52] Shi X, Leong KY, Ng HY. Anaerobic treatment of pharmaceutical wastewater: A critical review. Bioresour Technol 2017;245:1238–1244. [CrossRef]

[53] Hosseini AM, Bakos V, Jobbagy A, Tardy G, Mizsey P, Mako M, et al. Co-treatment and utilisation of liquid pharmaceutical wastes. Period Polytech 2011;55:3-10. [CrossRef]

[54] Mostofi A. Select issues in designing license contracts of strategic alliances in the pharmaceutical supply chain. Dissertation. Wellington: Victoria Univ; 2022.

[55] Enright AM, McHugh S, Collins G, O'FLaherty V. Low-temperature anaerobic biological treatment of solvent-containing pharmaceutical wastewater. Water Res 2005;39:4587–4596. [CrossRef]

[56] Sundararaman S, Sathiyapriya A. Acclimatization of an industrial pharmaceutical wastewater in an aerobic batch mode of operation. Int J Environ Res Dev 2016;6:1-10.

[57] Nguluka NC, Ochekpe NA, Odumosu PO. An assessment of pharmaceutical waste management in some Nigerian pharmaceutical industries. Afr J Biotechnol 2011;10:11259-11264. [CrossRef]

[58] Muruganandam B, Saravanane R, Lavanya M, Sivacoumar R. Effect of inoculum-substrate ratio on acclimatization of pharmaceutical effluent in an anaerobic batch reactor. J Environ Sci Eng 2008;50:191–196.

[59] Andersson S, Karlsson M. A comparative life cycle assessment of advanced processes for the removal of pharmaceutical residues in wastewater. Master's thesis. Gothenburg: Chalmers Unive; 2022.

[60] Pharmapproach. List of pharmaceutical companies in Nigeria. Available from: https://www.pharmapproach.com/list-of-pharmaceutical-companies-nigeria/4/. Accessed Jul 3, 2022.

[61] Zhu W, Bu F, Xu J, Wang Y, Xie L. Influence of lincomycin on anaerobic digestion: Sludge type, biogas generation, methanogenic pathway and resistance mechanism. Bioresour Technol 2021;329:124913. [CrossRef]

[62] Horner R. Global value chains, import orientation, and the state: South Africa's pharmaceutical industry. J Int Bus Policy 2022;5:68-87. [CrossRef]

[63] Njuguna AW, Mayabi AO, Ndirangu W. An investigation into the management of pharmaceutical wastewater in Kenya. In proceedings of the Sustainable Research and Innovation Conference; 2019 May 8–10; Kenya. 2019. p. 127-32.

[64] SaintyCo Pharma Process & Packaging. Top 200 pharmaceutical companies in South Africa. Available at: www.saintytec.com/pharmaceutical-companies-south-africa. Accessed on Jun 21, 2022.

[65] Justice. Pharmaceutical companies in Kenya (2022 list). Pharmchoices, Nairobi, Kenya; 2022. p. 1-18.

[66] Ogunbanwo OM, Kay P, Boxall AB, Wilkinson J, Sinclair CJ, Shabi RA, et al. High concentrations of pharmaceuticals in a nigerian river catchment. Environ Toxicol Chem 2022;41:551–558. [CrossRef]

[67] World Health Organization (WHO). Africa within the global pharmaceutical market. Available at: https://blog.private-sector-and-development.com/app/uploads/2019/02/PRO-Revue28-UK-key-figures.pdf. Accessed on Jul 2, 2024.

[68] Ussai S, Chillotti C, Stochino E, Deidda A, Ambu G, Anania L, et al. Building the momentum for a stronger pharmaceutical system in Africa. Int J Environ Res Public Health 2022;19:3313. [CrossRef]

[69] Holt T, Lahrichi M, Santos da Silva J. Africa: A continent of opportunity for pharma and patients. Available at: https://www.mckinsey.com/industries/life-sciences/our-insights/africa-a-continent-of-opportunity-for-pharma-and-patients. Accessed Jul 2, 2024.

[70] Fountoulakis MS, Stamatelatou K, Lyberatos G. The effect of pharmaceuticals on the kinetics of methanogenesis and acetogenesis. Bioresour Technol 2008;99:7083-7090. [CrossRef]

[71] Darwish M, Abuhabib AA, Mohammad H. Sustainable membranes with FNMs for pharmaceuticals and personal care products. In: Dutta S, Hussain CM, editor. Membranes with functionalized nanomaterials. 1st ed. Amsterdam, Netherlands: Elsevier; 2022. p. 275-328. [CrossRef]

[72] Fawzy ME, Abdelfattah I, Abuarab ME, Mostafa E, Aboelghait KM, El-Awady MH, et al. Sustainable approach for pharmaceutical wastewater treatment and reuse: Case study. J Environ Sci Technol 2018;11:209-219. [CrossRef]

[73] Mahtab MS, Farooqi IH. An overview of occurrence and removal of pharmaceuticals from sewage/

wastewater. In: Zhang T, editor. Sewage-Recent Advances, New Perspectives and Applications. IntechOpen; 2021.

[74] Mohan H, Rajput SS, Jadhav EB, Sankhla MS, Sonone SS, Jadhav S, et al. Ecotoxicity, occurrence, and removal of pharmaceuticals and illicit drugs from aquatic systems. Biointerface Res Appl Chem 2021;11:12530-12546. [CrossRef]

[75] Karungamye PN. Methods used for removal of pharmaceuticals from wastewater: A review. Appl J Environ Eng Sci 2020;6:412-428.

[76] xCarey DE, McNamara PJ. Altered antibiotic tolerance in anaerobic digesters acclimated to triclosan or triclocarban. Chemosphere 2016;163:22–26. [CrossRef]

[77] Bisognin RP, Wolff DB, Carissimi E, Prestes OD, Zanella R. Occurrence and fate of pharmaceuticals in effluent and sludge from a wastewater treatment plant in Brazil. Environ Technol 2021;42:2292–2303. [CrossRef]

[78] Frascaroli G, Reid D, Hunter C, Roberts J, Helwig K, Spencer J, et al. Pharmaceuticals in wastewater treatment plants: A systematic review on the substances of greatest concern responsible for the development of antimicrobial resistance. Appl Sci 2021;11:6670. [CrossRef]

[79] Luo X, Yang Q, Lin Y, Tang Z, Tomberlin JK, Liu W, et al. Black soldier fly larvae effectively degrade lincomycin from pharmaceutical industry wastes. J Environ Manage 2022;307:114539. [CrossRef]

[80] Campbell AJ. The behaviour of pharmaceuticals in anaerobic digester sludge. Master's thesis. Portsmouth: Univ of Portsmouth; 2013.

[81] Lankila A. Removal of pharmaceutical compounds by adsorption. Master's thesis. Lappeenranta: Lahti Univ; 2022.

[82] Zahedi S, Gros M, Balcazar JL, Petrovic M, Pijuan M. Assessing the occurrence of pharmaceuticals and antibiotic resistance genes during the anaerobic treatment of slaughterhouse wastewater at different temperatures. Sci Total Environ 2021;789:147910. [CrossRef]

[83] Song S, Jiang M, Yao J, Liu H, Dai X. Anaerobic digestion of spectinomycin mycelial residues pretreated by thermal hydrolysis: Removal of spectinomycin and enhancement of biogas production. Environ Sci Pollut Res Int 2020;27:39297–39307. [CrossRef]

[84] Cucina M, Zadra C, Marcotullio MC, Di Maria F, Sordi S, Curini M, et al. Recovery of energy and plant nutrients from a pharmaceutical organic waste derived from a fermentative biomass: Integration of anaerobic digestion and composting. J Environment Chem Eng 2017;5:3051–3057. [CrossRef]

[85] Mitchell SM, Ullman JL, Teel AL, Watts RJ, Frear C. The effects of the antibiotics ampicillin, florfenicol, sulfamethazine, and tylosin on biogas production and their degradation efficiency during anaerobic digestion. Bioresour Technol 2013;149:244–252. [CrossRef]

[86] Cetecioglu Z, Ince B, Gros M, Rodriguez-Mozaz S, Barceló D, Ince O, et al. Biodegradation and reversible inhibitory impact of sulfamethoxazole on the utilization of volatile fatty acids during anaerobic treatment of pharmaceutical industry wastewater. Sci Total Environ 2015;536:667–674. [CrossRef]

[87] Golub N, Ying Z, Kozlovets O, Levtun I, Ranra S. Wastewater purification from antibiotics with simultaneous biogas production. J Microbiol Biotechnol Food Sci 2020;10:170-175. [CrossRef]

[88] Lallai A, Mura G, Onnis N. The effects of certain antibiotics on biogas production in the anaerobic digestion of pig waste slurry. Bioresour Technol 2002;82:205–208. [CrossRef]

[89] Gadipelly C, Perez-Gonzalez A, Yadav GD, Ortiz I, Ibanez R, Rathod VK, et al. Pharmaceutical industry wastewater: Review of the technologies for water treatment and reuse. Ind Eng Chem Res 2014;53:11571-11592. [CrossRef]

[90] Amin MM, Hashemi H, Ebrahimi A, Ebrahimi A, Hashemi EH. Effects of oxytetracycline, tylosin, and amoxicillin antibiotics on specific methanogenic activity of anaerobic biomass. Int J Environ Health Eng 2012;1:1-37. [CrossRef]

[91] Koniuszewska I, Harnisz M, Korzeniewska E, Czatzkowska M, Jastzebski JP, Paukszto L, et al. The effect of antibiotics on mesophilic anaerobic digestion process of cattle manure. Energies 2021;14:1125. [CrossRef]

[92] Alenzi A, Hunter C, Spencer J, Roberts J, Craft J, Pahl O, et al. Pharmaceuticals effect and removal, at environmentally relevant concentrations, from sewage sludge during anaerobic digestion. Bioresour Technol 2021;319:124102. [CrossRef]

[93] Visca A, Barra Caracciolo A, Grenni P, Patrolecco L, Rauseo J, Massini G, et al. Anaerobic digestion and removal of sulfamethoxazole, enrofloxacin, ciprofloxacin and their antibiotic resistance genes in a full-scale biogas plant. Antibiotics (Basel) 2021;10:502. [CrossRef]

[94] Amin MM, Zilles JL, Greiner J, Charbonneau S, Raskin L, Morgenroth E. Influence of the antibiotic erythromycin on anaerobic treatment of a pharmaceutical wastewater. Environ Sci Technol 2006;40:3971–3977. [CrossRef]

[95] Aydin S, Ince B, Ince O. Inhibitory effect of erythromycin, tetracycline and sulfamethoxazole antibiotics on anaerobic treatment of a pharmaceutical wastewater. Water Sci Technol 2015;71:1620-1628. [CrossRef]

[96] Zeng S, Sun J, Chen Z, Xu Q, Wei W, Wang D, et al. The impact and fate of clarithromycin in anaerobic

digestion of waste activated sludge for biogas production. Environ Res 2021;195:110792. [CrossRef]
[97] Lehmann L, Bloem E. Antibiotic residues in substrates and output materials from biogas plants - Implications for agriculture. Chemosphere 2021;278:130425. [CrossRef]
[98] Adesina A, Sanni F. Pharmaceutical wastes management and the presence of pharmaceuticals in the environment of health facilities in Lagos state, Nigeria. Texila Int J Public Health 2018;6. [CrossRef]
[99] Sella CF, Carneiro RB, Sabatini CA, Sakamoto IK, Zaiat M. Can different inoculum sources influence the biodegradation of sulfamethoxazole antibiotic during anaerobic digestion? Braz J Chem Eng 2021;39:35–46. [CrossRef]
[100] Mahlaule-Glory LM, Mathobela S, Hintsho-Mbita NC. Biosynthesized bimetallic (ZnO-SnO2) nanoparticles for photocatalytic degradation of organic dyes and pharmaceutical pollutants. In: Pagano R, Valli L, Syrgiannis Z, editors. Catalysts 2022;12:334. [CrossRef]
[101] Caracciolo AB, Visca A, Massini G, Patrolecco L, Miritana VM, Grenni P. Environmental fate of antibiotics and resistance genes in livestock waste and digestate from biogas plants. Available at: https://kosmospublishers.com/environmental-fate-of-antibiotics-and-resistance-genes-in-livestock-waste-and-digestate-from-biogas-plants-2/. Accessed on Jul 3, 2024.
[102] Guo J, Ostermann A, Siemens J, Dong R, Clemens J. Short term effects of copper, sulfadiazine and difloxacin on the anaerobic digestion of pig manure at low organic loading rates. Waste Manag 2012;32:131–136. [CrossRef]
[103] Oliver JP, Gooch CA, Lansing S, Schueler J, Hurst JJ, Sassoubre L, et al. Invited review: Fate of antibiotic residues, antibiotic-resistant bacteria, and antibiotic resistance genes in US dairy manure management systems. J Dairy Sci 2020;103:1051–1071. [CrossRef]
[104] Yahia MB. An advanced physical modeling of adsorption mechanism of pharmaceutical compound on a biochar. AIP Adv 2022;12:035003. [CrossRef]
[105] Pavithra KG, Kumar PS, Rajan PS, Saravanan A, Naushad M. Sources and impacts of pharmaceutical components in wastewater and its treatment process: A review. Korean J Chem Eng 2017;34:2787-2805. [CrossRef]
[106] Bauer A, Amon T, Winckler C, Gans O, Scharf S. Effects of antibiotic residues in manure on biogas yield. Available at: https://boku.ac.at/fileadmin/data/H05000/H13000/Kooperation_BOKU-U/Poster_StratKoopBOKUU_antibiotics_2013_Bauer.pdf. Accessed on Jul 3, 2024.
[107] Chen Z, Wang H, Chen Z, Ren N, Wang A, Shi Y, et al. Performance and model of a full-scale up-flow anaerobic sludge blanket (UASB) to treat the pharmaceutical wastewater containing 6-APA and amoxicillin. J Hazard Mater 2011;185:905–913. [CrossRef]
[108] Saravanane R, Murthy DV, Krishnaiah K. Bioaugmentation and treatment of cephalexin drug-based pharmaceutical effluent in an upflow anaerobic fluidized bed system. Bioresour Technol 2001;76:279–281. [CrossRef]
[109] Sun H. Antibiotic resistance in biogas processes. Doctoral thesis. Uppsala: Swedish Univ; 2021.
[110] Nuengjamnong C, Rachdawong P, Chalermchaikit T. Effect of amoxicillin on biogas production and the Eschericia coli population in biogas systems treating swine wastewater. Thai J Vet Med 2010;40:57-62. [CrossRef]
[111] Li W, Qigui N, Hong Z, Zhe T, Yu Z, Yingxin G, et al. UASB treatment of chemical synthesis-based pharmaceutical wastewater containing rich organic sulfur compounds and sulfate and associated microbial characteristics. Chem Eng J 2015;260:55-63. [CrossRef]
[112] Gupta S, Chandra TS, Sharma A, Lokhande SK. Ozone-induced biodegradability enhancement and color reduction of a complex pharmaceutical effluent. J Int Ozone Assoc 2015;37:1-8. [CrossRef]
[113] Kayalvizhi N, Asha B. Role of volatile fatty acids in acidogenic and methanogenic reactor for treating pharmaceutical wastewater. Asian J Microbiol Biotechnol Environ Sci 2020;22:479-485.
[114] Kelbert M. Antineoplastic drugs: Effect of doxorubicin on enriched archaea culture from anaerobic digestion and potential degradation via an enzymatic process. Doctoral thesis. Florianópolis: Univ Federal de Santa Catarina; 2022.
[115] Ng KK, Shi X, Tang MKY, Ng HY. A novel application of anaerobic bio-entrapped membrane reactor for the treatment of chemical synthesis-based pharmaceutical wastewater. Sep Purif Technol 2014;132:634-643. [CrossRef]
[116] Pugazhendi A, Jamal MT, Al-Mur BA, Jeyakumar RB. Bioaugmentation of electrogenic halophiles in the treatment of pharmaceutical industrial wastewater and energy production in microbial fuel cell under saline condition. Chemosphere 2022;288:132515. [CrossRef]
[117] VEOLIA. Pharmaceutical manufacturing - Wastewater treatment guide. Available at: https://www.veoliawatertech.com/sites/g/files/dvc3601/files/document/2020/06/Veolia_Pharma_Guide_Wastewater_2020_HR_With_Links_0.pdf. Accessed Jul 3, 2024.
[118] Chittala G, Mogadati PS. Performance studies on a pharmaceutical wastewater treatment plant with a special reference to total dissolved solids removal. Int J Life Sci Biotechnol Pharma Res 2012;1:103-112.
[119] Hrenovic J, Stilinovic B, Dvoracek L. Use of prokaryotic and eukaryotic biotests to assess toxicity

of wastewater from pharmaceutical sources. Acta Chim Slov 2005;52:119-125.
[120] Menacherry SPM, Aravind UK, Aravindakumar CT. Oxidative degradation of pharmaceutical waste, theophylline, from natural environment. Atmosphere (Basel) 2022;13:835. [CrossRef]
[121] Chen YF, Ng WJ, Yap MGS. Performance of upflow anaerobic biofilter process in pharmaceutical wastewater treatment. Resour Conserv Recycl 1994;11:83-91. [CrossRef]
[122] Gulmez B, Ozturk I, Alp K, Arikan OA. Common anaerobic treatability of pharmaceutical and yeast industry wastewater. Water Sci Technol 1998;38:37-44. [CrossRef]
[123] Vijayan DS, Mohan A, Nivetha C, Sivakumar V, Devarajan P, Paulmakesh A, et al. Treatment of pharma effluent using anaerobic packed bed reactor. J Environ Public Health 2022;2022:4657628. [CrossRef]
[124] Ribeiro MHG, de A. Silva MC, Benetti AD. Anaerobic membrane bioreactor to remove pesticides and pharmaceuticals from wastewater: A bibliometric review. ICONASET-2023: Complexity and İmpact of Emerging Contaminants On Environment and Human Health, 2024. [CrossRef]
[125] Kumar V, Bansal V, Madhavan A, Kumar M, Sindhu R, Awasthi MK, et al. Active pharmaceutical ingredient (API) chemicals: A critical review of current biotechnological approaches. Bioengineered 2022;13:4309–4327. [CrossRef]
[126] Malmborg J, Magnér J. Pharmaceutical residues in sewage sludge: Effect of sanitization and anaerobic digestion. J Environ Manage 2015;153:1–10. [CrossRef]
[127] Mejías C, Martín J, Santos JL, Aparicio I, Alonso E. Occurrence of pharmaceuticals and their metabolites in sewage sludge and soil: A review on their distribution and environmental risk assessment. Trends Environ Anal Chem 2021;30:e00125. [CrossRef]
[128] Sreekanth D, Sivaramakrishna D, Himabindu V, Anjaneyulu Y. Thermophilic treatment of bulk drug pharmaceutical industrial wastewaters by using hybrid up flow anaerobic sludge blanket reactor. Bioresour Technol 2009;100:2534–2549. [CrossRef]
[129] Zhan H, Liang X, Wei Y, Zhuang X, Peng H, Zeng Z, et al. Utilization and valorization of pharmaceutical process residues: Current status and future trends. J Clean Prod 2024;438:140751. [CrossRef]
[130] Patel M, Kumar R, Kishor K, Mlsna T, Pittman CU Jr, Mohan D. Pharmaceuticals of emerging concern in aquatic systems: Chemistry, occurrence, effects, and removal methods. Chem Rev 2019;119:3510–3673. [CrossRef]
[131] Fountoulakis M, Drillia P, Stamatelatou K, Lyberatos G. Toxic effect of pharmaceuticals on methanogenesis. Water Sci Technol 2018;50:335-340. [CrossRef]
[132] Robertson KJ, Brar R, Randhawa P, Stark C, Baroutian S. Opportunities and challenges in waste management within the medicinal cannabis sector. Ind Crops Prod 2023;197:116639. [CrossRef]
[133] Wohde M, Berkner S, Junker T, Konradi S, Schwarz L, Düring RA. Occurrence and transformation of veterinary pharmaceuticals and biocides in manure: A literature review. Environ Sci Eur 2016;28:23. [CrossRef]
[134] Arcanjo GS, Dos Santos CR, Cavalcante BF, Moura GA, Ricci BC, Mounteer AH, et al. Improving biological removal of pharmaceutical active compounds and estrogenic activity in a mesophilic anaerobic osmotic membrane bioreactor treating municipal sewage. Chemosphere 2022;301:134716. [CrossRef]
[135] Reddy BV, Sandeep P, Ujwala P, Navaneetha K, Reddy KVR. Water treatment process in pharma industry: A review. Int J Pharm Biol Sci 2014;4:7-19.
[136] Lie M, Rubiyatno, Binhudayb FS, Thao NTT, Kristanti RA. Assessing the impact of pharmaceutical contamination in Malaysian groundwater: Risks, modelling, and remediation strategies. Trop Aquat Soil Pollut 2024;4:43-59, 2024. [CrossRef]
[137] Singh S, Pant A, Dutta K, Rani T, Vithanage M, Daverey A. Phytoremediation of pharmaceuticals and personal care products using the constructed wetland. Environ Chem Ecotoxicol 2024;6:104-116. [CrossRef]
[138] Abdelmigeed MO, Sadek AH, Ahmed TS. Novel easily separable core-shell Fe3O4/PVP/ZIF-8 nanostructure adsorbent: Optimization of phosphorus removal from fosfomycin pharmaceutical wastewater. RCS Adv 2022;12:12823-12842. [CrossRef]
[139] Javid F, Ang TN, Hanning S, Svirskis D, Burrell R, Taylor M, et al. Subcritical hydrothermal deconstruction of two hormones (adrenaline and progesterone) in pharmaceutical waste. J Supercrit Fluids 2022;179:105388. [CrossRef]
[140] Michael I, Ogbonna B, Sunday N, Anetoh M, Matthew O. Assessment of disposal practices of expired and unused medications among community pharmacies in Anambra state southeast Nigeria: A mixed study design. J Pharm Policy Pract 2019;12:12. [CrossRef]
[141] Azizan NAZ, Yuzir A, Abdullah N. Pharmaceutical compounds in anaerobic digestion: A review on the removals and effect to the process performance. J Environ Chem Eng 2021;9:105926. [CrossRef]
[142] Hao F. Research progress in pharmaceutical wastewater treatment technology. E3S Web Conf 2019;118:04019. [CrossRef]
[143] Cha YS, Yoon SU, Kim CG. Studies on influence and fate of carbamazepine in anaerobic digestion of sludge. J Environ Biol 2016;37:37–42.
[144] Vaughan M. uPOPs prevention and chemical awareness: Elements of a general awareness campaign. Available at: https://www.sprep.org/attachments/Reports/GEFPAS_Pollutant_Awareness_Camapign.pdf. Accessed on Jul 3, 2024.

[145] Šefčovičová K, Veronika K, Juraj M, Maros S, Igor B, Andrey K. Influence of selected pharmaceuticals on biogas production in mesophilic anaerobic fermentation. Res Pap 2021;29:149-157. [CrossRef]
[146] Klatte S, Schaefer HC, Hempel M. Pharmaceuticals in the environment-A short review on options to minimize the exposure of humans, animals and ecosystems. Sustain Chem Pharm 2016;5:61-66. [CrossRef]
[147] Colella K. Time trends of pharmaceuticals in wastewater treatment plant effluent with sources from pharmaceutical manufacturing facilities and hospitals. Master's thesis. New York: Stony Brook Univ; 2014.
[148] Danbauchi ES. Evaluation of lower Usuma Dam water quality for domestic supply (FCT) Abuja, Nigeria. Int J Res Sci Innov. 2020;7:219-224.
[149] Ilechukwu I. We found traces of drugs in a dam that supplies Nigeria's capital city. Available at: https://theconversation.com/we-found-traces-of-drugs-in-a-dam-that-supplies-nigerias-capital-city-161927. Accessed on Jul 3, 2024.
[150] Adegbe EA, . Pharmaceutical compounds in wastewater discharged from a University Teaching Hospital liquid waste treatment plant. Niger Res J Chem Sci 2019;7:256-261.
[151] Naveenkumar M, Anantharaj C, Porkodi N, Senthilkumar K, Nandakumar NP. A review on pharmaceutical wastewater treatment using biological process-benefits and opportunities. in Development in Wastewater Treatment Research and Processes-Emerging Technologies for Removal of Pharmaceuticals and Personal Care Products: State of the Art, Challenges and Future Perspectives, 2024, pp. 99-114. [CrossRef]
[152] Ameri B, Salah H. Analogous study of biogas production by anaerobic digestion of sewage treatment plant sludge , proposal of universal dimensionless models. Energy Sci Eng 2022;11;2366–2384. [CrossRef]
[153] Thomas A, et al. Treatment of pharmaceutical waste water treatment. Int J Eng Res Technol 2021;10:733-736.
[154] Mehmood T, Nadeem F, Bilal M, Meer B, Meer, K Qamar SA. Biological treatment of pharmaceutical wastes. In: Singh P, Verma P, Singh R, Ahamad A, Batalhao ACS, editors. Waste Management and Resource Recycling in the Developing World. 1st ed. Amsterdam, Netherlands: Elsevier. 2023. pp. 577-600. [CrossRef]
[155] Kamali M, Aminabhavi TM, Costa MEV, Islam SU, Appels L, Dewil R. Pharmaceutically active compounds in anaerobic digestion processes-Biodegradation and fate. In: Advanced Wastewater Treatment Technologies for the Removal of Pharmaceutically Active Compounds. Cham: Springer; 2023. pp. 91-106. [CrossRef]
[156] Iliopoulou A, Arvaniti OS, Deligiannis M, Gatidou G, Vyrides I, Fountoulakis MS, et al. Combined use of strictly anaerobic MBBR and aerobic MBR for municipal wastewater treatment and removal of pharmaceuticals. J Environ Manage 2023;343:118211. [CrossRef]
[157] Inanc B, Calli B, Alp K, Ciner F, Mertoglu B, Ozturk I. Toxicity assessment on combined biological treatment of pharmaceutical industry effluents. Water Sci Technol 2002;45:135–142. [CrossRef]
[158] Buitrón G, Melgoza RM, Jiménez L. Pharmaceutical wastewater treatment using an anaerobic/aerobic sequencing batch biofilter. J Environ Sci Health A Tox Hazard Subst Environ Eng 2003;38:2077–2088. [CrossRef]
[159] Huang B, Wang H, Cui D, Zhang B, Chen Z-B, Wang A-J. Treatment of pharmaceutical wastewater containing β-lactams antibiotics by a pilot-scale anaerobic membrane bioreactor (AnMBR). Chem Eng J 2018;341:238-247. [CrossRef]
[160] An Z, Junjie Z, Min Z, Yan Z, Xiaomei S, Hongjun L, et al. Anaerobic membrane bioreactor for the treatment of high-strength waste/wastewater: A critical review and update. Chem Eng J 2023;470:144322. [CrossRef]
[161] Schlott DA, Charbonneau SG, Greiner JA, Green RE, Quane DE, Robertson WM. Design, construction & start-up of an anaerobic treatment system for pharmaceutical wastewater. In proceedings of the 43rd Industrial Waste Conference; 1998 May 10–12; Indiana, USA. 1989.
[162] Murugesan MP, Akilamudhan P, Sureshkumar A, Arunkarhikeya G. Treatment of hospital and biomedical waste effluent using HUASB reactor Int J Innov Sci Res 2014;11:379-386.
[163] Li Y, Li C, Wang Z, Liu Y, Jia Y, Li F, et al. Navigating the complexity of pharmaceutical wastewater treatment by 'effective strategy, emerging technology, and sustainable solution. J Water Process Eng 2024;63:105404. [CrossRef]
[164] Yin F, Wang D, Li Z, Ohlsen T, Hartwig P, Czekalla S. Study on anaerobic digestion treatment of hazardous colistin sulphate contained pharmaceutical sludge. Bioresour Technol 2015;177:188–193. [CrossRef]
[165] Liu H, Xu G, Li G. Autocatalytic sludge pyrolysis by biochar derived from pharmaceutical sludge for biogas upgrading. Energy 2021;229:120802. [CrossRef]
[166] Ouyang J, Zhou L, Liu Z, Heng JYY, Chen W. Biomass-derived activated carbons for the removal of pharmaceutical micropollutants from wastewater: A review. Sep Purif Technol 2020;253:117536. [CrossRef]
[167] Saravanane R, Murthy DVS, Krishnaiah K. Assessment of toxicity and anaerobic degradation of anti-osmotic drug based pharmaceutical effluent in an upflow anaerobic fluidized bed system. Glob Nest Int J 2000;2:149-158. [CrossRef]

[168] Mantovani M, Rossi S, Ficara E, Collina E, Marazzi F, Lasagni M, et al. Removal of pharmaceutical compounds from the liquid phase of anaerobic sludge in a pilot-scale high-rate algae-bacteria pond. Sci Total Environ 2024;908:167881. [CrossRef]

[169] Kasulla S, Malik SJ. Unlocking the true energy potential of waste water treatment plants. Available at: https://www.brenstech.com/2023/10/03/unlocking-the-true-energy-potentials-of-waste-water-treatment-plants/. Accessed on Jul 3, 2024.

[170] Freitas RXA, Borges LA, de Souza HF, Colen F, Cangussu ASR, Sobrinho EM, et al. Characterization of the primary sludge from pharmaceutical industry effluents and final disposition. Processes 2019;7:231. [CrossRef]

[171] Ali Q, Zainab R, Badshah M, Sarwar W, Khan S, Mustafa G, et al. Prospecting the biodegradation of ciprofloxacin by Stutzerimonas stutzeri R2 and Exiguobacterium indicum strain R4 isolated from pharmaceutical wastewater. H_2Open J 2024;7:149-162. [CrossRef]

[172] Pandis PK, Kalogirou C, Kanellou E, Vaitsis C, Savvidou MG, Sourkouni G, et al. Key points of advanced oxidation processes (AOPs) for wastewater, organic pollutants and pharmaceutical waste treatment: A mini review. Chemengineering 2022;6:8. [CrossRef]

[173] Carballa M, Manterola G, Larrea L, Ternes T, Omil F, Lema JM. Influence of ozone pre-treatment on sludge anaerobic digestion: Removal of pharmaceutical and personal care products. Chemosphere 2007;67:1444–1452. [CrossRef]

[174] Wen S, Chen L, Li W, Ren H, Li K, Wu B, et al. Insight into the characteristics, removal, and toxicity of effluent organic matter from a pharmaceutical wastewater treatment plant during catalytic ozonation. Sci Rep 2018;8:9581. [CrossRef]

[175] Sörensen M, Zegenhagen F, Weckenmann J. State of the art wastewater treatment in pharmaceutical and chemical industry by advanced oxidation. Pharmind Prax 2015;77:594-607.

[176] Remya RR, Julius A, Suman TY, Mohanavel V, Karthick A, Pazhanimuthu C, et al. Role of nanoparticles in biodegradation and their importance in environmental and biomedical applications. J Nanomater 2022;2022:6090846. [CrossRef]

[177] Zhang J, Peng Y, Li X, Du R. Feasibility of partial-denitrification/ anammox for pharmaceutical wastewater treatment in a hybrid biofilm reactor. Water Res 2022;208:117856. [CrossRef]

[178] Maleki Shahraki Z, Mao X. Biochar application in biofiltration systems to remove nutrients, pathogens, and pharmaceutical and personal care products from wastewater. J Environ Qual 2022;51:129–151. [CrossRef]

[179] Ganesan S, Shanmugam S, Alagarasan JK, Lingassamy AP, Savunthari KV, Lo HM, et al. Novel African tulip fruit waste-derived biochar nanostructural materials for the removal of widespread pharmaceutical contaminant in wastewaters. Biomass Convers Bior 2023;13:13513–13525. [CrossRef]

[180] Ihsanullah I, Khan MT, Zubair M, Bilal M, Sajid M. Removal of pharmaceuticals from water using sewage sludge-derived biochar: A review. Chemosphere 2022;289:133196. [CrossRef]

[181] Sheng X, Wang J, Cui Q, Zhang W, Zhu X. A feasible biochar derived from biogas residue and its application in the efficient adsorption of tetracycline from an aqueous solution. Environ Res 2022;207:112175. [CrossRef]

[182] Al-Samrraie LA, Alrawashdeh KAB, Al-Issa HA, Shakhatreh S, Hussien AA, Qasem I. Improve heavy metals and pollutants removal from the pharmaceuticals wastewater using Washingtonia robusta: New extraction process. Civ Environ Eng 2022;18:340–349. [CrossRef]

[183] Madikizela LM, Pakade VE. Trends in removal of pharmaceuticals in contaminated water using waste coffee and tea-based materials with their derivatives. Water Environ Res 2023;95:e10857. [CrossRef]

[184] Al-Mashaqbeh O, Alsalhi L, Salaymeh L, Dotro G, Lyu T. Treatment of pharmaceutical industry wastewater for water reuse in Jordan using hybrid constructed wetlands. Sci Total Environ 2024;939:173634. [CrossRef]

[185] Gnanavel G, Muthusamy P. Pharmaceutical industry wastewater treatment using atmospheric air and pure oxygen. Int Acad Sci Eng Technol 2018;7:1-6.

[186] Mohan SV, Prakasham RS, Satyavathi B, Annapurna J, Ramakrishna SV. Biotreatability studies of pharmaceutical wastewater using an anaerobic suspended film contact reactor. Water Sci Technol 2001;43:271–276. [CrossRef]

[187] Chen Z, Wang Y, Li K, Zhou H. Effects of increasing organic loading rate on performance and microbial community shift of an up-flow anaerobic sludge blanket reactor treating diluted pharmaceutical wastewater. J Biosci Bioeng 2024;118:284-288. [CrossRef]

[188] Chen Z, Xu J, Hu D, Cui Y, Wu P, Hui Ge, et al. Performance and kinetic model of degradation on treating pharmaceutical solvent wastewater at psychrophilic condition by a pilot-scale anaerobic membrane bioreactor. Bioresour Technol 2018;269:319328. [CrossRef]

[189] Ng KK, Shi X, Ng HY. Evaluation of system performance and microbial communities of a bioaugmented anaerobic membrane bioreactor treating pharmaceutical wastewater. Water Res 2015;81:311–324. [CrossRef]

[190] Dutta K, Lee MY, Lai WW, Lee CH, Lin AY, Lin CF, et al. Removal of pharmaceuticals and organic matter from municipal wastewater using two-stage anaerobic fluidized membrane bioreactor. Bioresour Technol 2014;165:42–49. [CrossRef]

[191] Mullai P, Solaiappan V, Sabarathinam PL. Biogas production kinetics in an anaerobic multiphase hybrid reactor treating antibiotic industry wastewater. Desalin Water Treat 2018;122:247–253. [CrossRef]
[192] Nandy T, Kaul SN, Szpyrkowicz L. Treatment of herbal pharmaceutical wastewater with energy recovery. Int J Environ Stud 1998;54:83-105. [CrossRef]
[193] Svojitka J, Dvorak L, Studer M, Straub JO, Frömelt H, Wintgens T. Performance of an anaerobic membrane bioreactor for pharmaceutical waste-water treatment. Bioresour Technol 2017;229:180–189. [CrossRef]
[194] Wang KM, Zhou LX, Ji KF, Xu SN, Wang JD. Evaluation of a modified internal circulation (MIC) anaerobic reactor for real antibiotic pharmaceutical wastewater treatment: Process performance, microbial community and antibiotic resistance genes evolutions. J Water Process Eng 2022;48:102914. [CrossRef]
[195] Kumar P, Meena M, Kavar AB, Nama P, Pathak A, Varma R, et al. Experimental study to optimise the treatment efficacy of pharmaceutical effluents by combining electron beam irradiation with conventional techniques. Available at: https://arxiv.org/abs/2109.02479. Accessed on Jul 3, 2024.
[196] Kumar P, Mandal MK, Pal S, Chaudhuri H, Dubey KK. Membrane bioreactor for the treatment of emerging pharmaceutical compounds in a circular bioeconomy. In: Varjani S, Pandey A, Bhaskar T, Mohan SV, Tsang DCW, editors. Biomass, Biofuels, Biochemicals, Circular Bioeconomy: Technologies for Waste Remediation. Amsterdam, Netherlands: Elsevier; 2022. pp. 203-221. [CrossRef]
[197] Hu D, Min H, Chen Z, Zhao Y, Cui Y, Zou X, et al. Performance improvement and model of a bio-electrochemical system built-in up-flow anaerobic sludge blanket for treating β-lactams pharmaceutical wastewater under different hydraulic retention time. Water Res 2019;164:114915. [CrossRef]
[198] Nandy T, Kaul SN. Anaerobic pre-treatment of herbal-based pharmaceutical wastewater using fixed-film reactor with recourse to energy recovery. Water Res 2001;35:351–362. [CrossRef]
[199] Fazal S, Zhang B, Zhong Z, Gao L, Lu X. Membrane separation technology on pharmaceutical wastewater by using MBR (Membrane Bioreactor). J Environ Prot 2015;6:299-307. [CrossRef]
[200] Xiao Y, Hazarki Y, de Araujo C, Chun Chau S, Stuckey DC. Removal of selected pharmaceuticals in an anaerobic membrane bioreactor (AnMBR) with/without powdered activated carbon (PAC). Chem Eng J 2017;321:335–345. [CrossRef]
[201] Mestre AS, Viegas RMC, Mesquita E, Rosa MJ, Carvalho AP. Engineered pine nut shell derived activated carbons for improved removal of recalcitrant pharmaceuticals in urban wastewater treatment. J Hazard Mater 2022;437:129319. [CrossRef]
[202] Baaloudj O, Badawi AK, Hamza K, Yasmine B, Raouf H, Noureddine N, et al. Techno-economic studies for a pilot-scale Bi12TiO20 based photocatalytic system for pharmaceutical wastewater treatment: From laboratory studies to commercial-scale applications. J Water Process Eng 2022;48:102847. [CrossRef]
[203] Łubek-Nguyen A, Ziemichod W, Olech M. Application of enzyme-assisted extraction for the recovery of natural bioactive compounds for nutraceutical and pharmaceutical applications. Appl Sci 2022;12:3232. [CrossRef]
[204] Taylor P, Saravanane R, Murthy DVS, Krishnaiah K. Bioaugmentation and anaerobic treatment of pharmaceutical effluent in fluidized bed reactor. J Environ Sci Heal Part A Toxic/Hazardous Subst Environ Eng 2021;36:779-791. [CrossRef]
[205] Abu Mhady AI, Awad MA, Al-Aghah MR, El-Nahhal YZ. Assessment of medical waste Dehghani MH, Azam K, Changani F, Dehghani Fard E. Assessment of medical waste management in educational hospitals of Tehran university medical sciences. Iran J Environ Heal Sci Eng 2008;5:131-136.
[206] Dehghani MH, Azam K, Changani F, Fard ED. Assessment of medical waste management in educational hospitals of Tehran university medical sciences. Iran J Environ Heal Sci Eng 2008;5:131-136.
[207] Mohammed AMA, Kabbashi FMA, Hamad HK. Production of biogas from biomedical waste (blood). Master's thesis. Khartom: Sudan Univ; 2017.
[208] Health Care Without Harm. Non-incineration medical waste treatment technologies in Europe. Available at: https://www.env-health.org/IMG/pdf/altech_Europe_updated_version_10_12_2004.pdf. Accessed on Jul 3, 2024.
[209] Kabbashi FM, Hassan E. Methane production from biomedical waste (blood). Int J Energy Environ Eng 2018;12:642-649.
[210] Kularatne RKA. Biomedical waste generation at Ayurveda hospitals in South Asia: A mini review of the composition, quantities and characteristics. Waste Manag Res 2024;42:95–110. [CrossRef]
[211] Rana A, Sharma N, Hasan I. A review on hospital waste as a potential environmental pollution and their remediation mechanisms. AIP Conf Proc 2023;2535:020014. [CrossRef]
[212] Babu BR, Parende AK, Rajalakshmi R, Suriyakala P, Volga M. Management of biomedical waste in India and other countries: A review. J Int Environ Appl Sci 2009;4:65-78.
[213] Burik A. Microbes come to the rescue to reduce hospital waste. Available at: https://www.labiotech.eu/trends-news/pharmafilter-microbes-reduce-hospital-waste/. Accessed on Jul 3, 2024.
[214] Ejaeta O. National healthcare waste management plan. Federal Ministry of Health, Nigeria; 2008.

[215] Anitha J, Jayraaj IA. Isolation and identification of bacteria from biomedical waste (BMW). Int J Pharm Pharm Sci 2012;4:286-388.
[216] Longe EO, Williams A. A preliminary study of medical waste management in Lagos metropolis, Nigeria. Iran J Environ Heal Sci Eng 2006;3:133-139.
[217] Hou Y, Linlin J, Wenting M, Jian Li H. Analysing the factors affecting medical waste generation in China. Sustain Chem Pharm 2023;32:100975. [CrossRef]
[218] Wei Y, Cui M, Ye Z, Guo Q. Environmental challenges from the increasing medical waste since SARS outbreak. J Clean Prod 2021;291:125246. [CrossRef]
[219] Gao Q, Shi Y, Mo D, Nie J, Yang M, Rozelle S, et al. Medical waste management in three areas of rural China. PLoS One 2018;13:e0200889. [CrossRef]
[220] Zhimin M. Waste mismanagement: China's struggle with medical trash. Available at: https://www.wilsoncenter.org/publication/waste-mismanagement-chinas-struggle-medical-trash. Accessed on Jul 3, 2024.
[221] Marfe G, Perna S, Hermann A. Challenges in healthcare waste management of the UN 2030 agenda in the COVID-19 Era. Am J Environ Sci 2022;18:20-41. [CrossRef]
[222] Thomas TA. Recycling: Wealth from waste. Curr Med Issues 2017;15:252-256. [CrossRef]
[223] Giakoumakis G, Politi D, Sidiras D. Medical waste treatment technologies for energy, fuels, and materials production: A review. Energies 2021;14:8065. [CrossRef]
[224] Mohiuddin A. Medical waste: A nobody's responsibility after disposal. Int J Environ Sci Nat Resour 2018;15:45-51. [CrossRef]
[225] Yi TC, Jusoh MNH. Overview of clinical waste management in Malaysia. Front Water Environ 2021;1:47-57.
[226] Coker AO, Sangodoyin AY, Ogunlowo OO. Managing hospital wastes in Nigeria. Available at: https://wedc-knowledge.lboro.ac.uk/resources/conference/24/Coker.pdf. Accessed Jul 3, 2024.
[227] Ignou AA. Safe management of wastes from health-care activities, 2nd ed. Malta: World Health Organization, 2012.
[228] Stringer R. Medical waste and human rights. Available at: https://noharm-europe.org/sites/default/files/documents-files/1684/MedWaste_Human_Rights_Report.pdf. Accessed on Jul 3, 2024.
[229] Chisholm JM, Zamani R, Negm AM, Said N, Abdel Daiem MM, Dibaj M, et al. Sustainable waste management of medical waste in African developing countries: A narrative review. Waste Manag Res 2021;39:1149–1163. [CrossRef]
[230] Yong Z, Gang X, Guanxing W, Tao Z, Dawei J. Medical waste management in China: A case study of Nanjing. Waste Manag 2009;29:1376–1382. [CrossRef]
[231] Negishi R, Kawahara K. Infectious waste management in Japan: Assessment of current trends in waste measurement and reporting in general and psychiatric hospitals. J Mater Cycles Waste Manag 2022;25:421–429. [CrossRef]
[232] Giacchetta G, Marchetti B. Medical waste management: A case study in a small size hospital of central Italy. Strat Outsource Int J 2013;6:65-84. [CrossRef]
[233] Hassan MF, Shareefdeen Z. Recent developments in sustainable management of healthcare waste and treatment technologies. J Sustain Dev Energy Water Environ Syst 2022;10:1090384. [CrossRef]
[234] Dhanraj K. Perceptions of the pharmaceutical industry and regulators in South Africa towards registration harmonisation in the Southern African development community (SADC). Available at: https://etd.uwc.ac.za/handle/11394/7956. Accessed on Jul 3, 2024.
[235] Savitha KL, Joseph TJ. Efficiency of hospital waste management in Kerala: An analysis based on hospital ownership. Int J Res Anal Rev 2018;5:239-244.
[236] Ezirim I, Agbo F. Role of national policy in improving health care waste management in Nigeria. J Health Pollut 2018;8:180913. [CrossRef]
[237] Manegdeg F, Coronado LO, Paña R. Medical waste treatment and electricity generation using pyrolyzer-rankine cycle for specialty hospitals in Quezon city, Philippines. IOP Conf Ser 2020;463:012180. [CrossRef]
[238] Capoor MR, Bhowmik KT. Current perspectives on biomedical waste management: Rules, conventions and treatment technologies. Indian J Med Microbiol 2017;35:157–164. [CrossRef]
[239] Coker A, Sangodoyin A, Sridhar M, Booth C, Olomolaiye P, Hammond F. Medical waste management in Ibadan, Nigeria: Obstacles and prospects. Waste Manag 2009;29:804–811. [CrossRef]
[240] Honest A, Saria J. Performance of experimental bio-digestion for pathological and biodegradable waste management at Mwananyamala Regional Referral Hospital Tanzania. J Environ Prot 2020;11:838-847. [CrossRef]
[241] Songa SW. Placenta disposal to produce biogas in 10 referral hospitals. IPP Media, Dar es Salaam. 2022 May 12;1-5.
[242] Kellner C. Monitoring the placenta digester at Mwananyamala Referral Hospital; Dar es Salaam. 2019. Available at: http://greenhealthcarewaste.org/wp-content/uploads/2020/12/Tanzania-Monitoring-the-Placenta-Digester-at-Mwananyamala-Referral-Hospital.pdf. Accessed on Jul 3, 2024.
[243] Kellner C. Biogas plants at Sinza hospital; Dar es Salaam. Available at: https://greenhealthcarewaste.org/wp-content/uploads/2020/12/Tanzania-Report-Biogas-Plants-at-Sinza-Hospital.pdf. Accessed on Jul 3, 2024.

[244] Yeo S. Placenta used to generate clean energy in Filipino hospital. Available at: https://www.climatechangenews.com/2013/08/29/placenta-used-to-generate-clean-energy-in-filipino-hospital/. Accessed on Jul 3, 2024.
[245] Shahi PK. Kalikot hospital to run biogas plant. Available at: https://myrepublica.nagariknetwork.com/news/kalikot-hospital-to-run-biogas-plant/. Accessed Jul 3, 2024.
[246] The Indian Express (Express News Service). Holy family hospital starts Rs 13-lakh biogas plant to convert kitchen waste into gas for cooking purposes. Available at: https://indianexpress.com/article/cities/mumbai/holy-family-hospital-starts-rs-13-lakh-biogas-plant-5201852/. Accessed on Jul 3, 2024.
[247] Dhakal N, Karki AB, Nakarmi M. Waste to energy: Management of biodegradable healthcare waste through anaerobic digestion. Nepal J Sci Technol 2015;16:41-48. [CrossRef]
[248] Rahman KM, Melville L. An investigation into the conversion of non-hazardous medical wastes into biogas-A case study from the Health and Family Planning Sector in Bangladesh. Processes 2023;11:1494. [CrossRef]
[249] Fáberová M, Ivanová L, Szabová P, Štolcová M, Bodík I. The influence of selected pharmaceuticals on biogas production from laboratory and real anaerobic sludge. Environ Sci Pollut Res Int 2019;26:31846–31855. [CrossRef]
[250] Wang C, Jianfeng L, Qiumin L, Li H, Changmei W, Kai W, et al. A review of the effects of antibiotics on the anaerobic digestion of swine waste. Curr Opin Environ Sci Health 2021;25:100312. [CrossRef]
[251] Stergar V, Konèan JZ. The determination of anaerobic biodegradability of pharmaceutical waste using advanced bioassay technique. Chem Biomol Eng 2002;16:17-24.
[252] Díaz-Cubilla M, Letón P, Luna-Vázquez C, Marrón-Romera M, Boltes K. Effect of carbamazepine, ibuprofen, triclosan and sulfamethoxazole on anaerobic bioreactor performance: Combining cell damage, ecotoxicity and chemical information. Toxics 2022;10:42. [CrossRef]
[253] Nacheva PM, Peña-Loera B, Moralez-Guzmán F. Treatment of chemical-pharmaceutical wastewater in packed bed anaerobic reactors. Water Sci Technol 2006;54:157–163. [CrossRef]
[254] Aski AL, Borghei A, Zenouzi A, Ashrafi N, Taherzadeh MJ. Steam explosion pretreatment of sludge for pharmaceutical removal and heavy metal release to improve biodegradability and biogas production. Fermentation 2020;6:34. [CrossRef]
[255] Chen Z, Li X, Hu D, Cui Y, Gu F, Jia F, et al. Performance and methane fermentation characteristics of a pilot scale anaerobic membrane bioreactor (AnMBR) for treating pharmaceutical wastewater containing m-cresol (MC) and iso-propyl alcohol (IPA). Chemosphere 2018;206:750–758. [CrossRef]
[256] Gogoi M, Goswami R, Hazarika S. Membrane-based treatment of wastewater generated in pharmaceutical and textile industries for a sustainable environment. In: Verma S, Khan R, Mili M, Hashmi SAR, Srivastava AK, editors. Advanced Materials from Recycled Waste. 1st ed. Amsterdam, Netherlands: Elsevier; 2023. p. 87–109. [CrossRef]
[257] Ricky R, Shanthakumar S. Phycoremediation integrated approach for the removal of pharmaceuticals and personal care products from wastewater - A review. J Environ Manage 2022;302:113998. [CrossRef]
[258] Carballa M, Omil F, Ternes T, Lema JM. Fate of pharmaceutical and personal care products (PPCPs) during anaerobic digestion of sewage sludge. Water Res 2007;41:2139–2150. [CrossRef]
[259] Perez-Lemus N, Lopez-Serna R, Perez-Elvira SI, Barrado E. Analysis of 60 pharmaceuticals and personal care products in sewage sludge by ultra-high performance liquid chromatography and tandem mass spectroscopy. Microchem J 2022;175:107148. [CrossRef]
[260] Gaballah MS, Chand H, Guo J, Zhang C. Mixed veterinary antibiotics removal and effects on anaerobic digestion of animal wastes: Current practices and future perspectives. Chem Eng J 2024;483:149131. [CrossRef]
[261] Nesse AS, Jasinska A, Stoknes K, Aanrud SG, Ogner Risinggård K, Kallenborn R, et al. Low uptake of pharmaceuticals in edible mushrooms grown in polluted biogas digestate. Chemosphere 2024;351:141169. [CrossRef]
[262] Ismail ZZ, Talib AR. Recycled medical cotton industry waste as a source of biogas recovery. J Clean Prod 2016;112:4413–4418. [CrossRef]
[263] Stringer R. A win-win for disposing medical waste with biodigestion. Available at: https://www.greenpolicyplatform.org/blog/win-win-disposing-medical-waste-biodigestion. Accessed on Jul 3, 2024.
[264] Gustavsson LK, Heger S, Ejlertsson J, Ribe V, Hollert H, Keiter SH. Industrial sludge containing pharmaceutical residues and explosives alters inherent toxic properties when co-digested with oat and post-treated in reed beds. Environ Sci Eur 2014;26:8. [CrossRef]
[265] Dai C, Yang L, Wang J, Li D, Zhang Y, Zhou X. Enhancing anaerobic digestion of pharmaceutical industries wastewater with the composite addition of zero valent iron (ZVI) and granular activated carbon (GAC). Bioresour Technol 2022;346:126566. [CrossRef]
[266] Embio Limited. Energy recovery from pharmaceutical waste. Available at: https://www.mahaurja.com/meda/data/off_grid_bio_energy/Success%20Pharmaceutical%20Waste.pdf. Accessed on Jul 3, 2024.

[267] Krishna N. Case study-Biogas production from pharmaceutical waste. Available at: https://biogas-india.com/case-study-biogas-production-from-pharmaceutical-waste/. Accessed on Jul 3, 2024.
[268] Czubaszek R. The assessment of the suitability of lemon balm and alder buckthorn wastes for the biogas production. J Ecol Eng 2019;20:152-158. [CrossRef]
[269] Adetunji CO, Olaniyan OT, Anani OA, Bodunrinde RE, Osemweige OO, Ubi BE. Integrated processes for production of pharmaceutical products from agro-wastes. Biomass Biofuels Biochem; 2022;2022:439–461. [CrossRef]
[270] Sienkiewicz A, Piotrowska-Niczyporuk A, Bajguz A. Herbal industry wastes as potential materials for biofuel production. Proceedings 2020;51:6. [CrossRef]
[271] Fardad K, et al. Biodegradation of medicinal plants waste in an anaerobic digestion reactor for biogas production Document Other les. Comput Mater Contin 2018;55:318–392.
[272] Yitayal A, Mekibib D, Araya A. Study on biogas production potential of leaves of Justicia schimperiana and macro-nutrients on the slurry. Int J Waste Resour 2017;7:294.
[273] Patel S, Das P, Priyadarshi M, Babbar M, Hussain A, Bharat TV. Anaerobic digestion of herbal waste: A waste to energy option. Environ Monit Assess 2024;196:600. [CrossRef]
[274] Lewicki A, Piotrowska-Niczyporuk A, Bajguz A. The biogas production from herbs and waste from herbal industry. J Res Appl Agric Eng 2013;58:114-117.
[275] Zhang H, Yin M, Li S, Zhang S, Han G. The removal of erythromycin and its effects on anaerobic fermentation. Int J Environ Res Public Health 2022;19:7256. [CrossRef]
[276] Kim H, Choi H, Lee C. The potential use of human urine as a solvent for biogas upgrading. J Water Process Eng 2020;36:101343. [CrossRef]
[277] Sau SK, Mann TK, Giri A, Nandi PK. Effect of human urine during production of methane from boiled rice. Int J Sci Res 2013;2:60-64.
[278] The Guardian Newspapers. Generating electricity, cooking gas from urine, biodegradable waste. Available at: https://guardian.ng/generating-electricity-cooking-gas-from-urine-biodegradable-waste/#google_vignette. Accessed on Jul 3, 2024.
[279] Appala VNSG, Pandhare NN, Bajpai S. Mathematical models for optimization of anaerobic digestion and biogas production. In: Nandabalan YK, Garg VK, Labhsetwar NK, Singh A, editors. Zero Waste Biorefinery. Singapore: Springer; 2022. p. 575-591. [CrossRef]
[280] Rorke DCS, Lekha P, Kana GEB, Sithole BB. Effect of pharmaceutical wastewater as nitrogen source on the optimization of simultaneous saccharification and fermentation hydrogen production from paper mill sludge. 2022;25:100619. [CrossRef]
[281] Etheridge SP. Biogas applications. Available at: https://cetesb.sp.gov.br/biogas/wp-content/uploads/sites/3/2014/01/aplicacoes_do_biogas_na_europa_stephen_etheridge.pdf. Accessed on Jul 3,2024.
[282] Sapkota B, Pariatamby A. Pharmaceutical waste management system - Are the current techniques sustainable, eco-friendly and circular? A review. Waste Manag 2023;168:83–97. [CrossRef]
[283] Auta A, Omale S, Shalkur D, Abiodun AH. Unused medicines in Nigerian households: Types and disposal practices. J Pharmacol Pharmacother 2011;2:195–196. [CrossRef]
[284] WHO. Safe disposal of unwanted pharmaceuticals in and after emergencies. Pan Am J Public Heal 2000;7:205-208. [CrossRef]
[285] Okoro RN, Peter E. Household medicines disposal practices in Maiduguri, North-Eastern Nigeria. Int J Heal Life Sci 2019;6:e97085. [CrossRef]
[286] Gerwig K, Permanente K. Waste management & healthcare. Available at: https://noharm-global.org/hcwh-content-tags/health-care-waste-management?page=1. Accessed on Jul 3, 2024.
[287] Obayomi KS, Lau SY, Mayowa IE, Danquah MK, Zhang JC, Tung M, et al. Recent advances in graphene-derived materials for biomedical waste treatment. J Water Process Eng 2023;51:103440. [CrossRef]
[288] Awodele O, Adewoye AA, Oparah AC. Assessment of medical waste management in seven hospitals in Lagos, Nigeria. BMC Public Health 2016;16:269. [CrossRef]
[289] Nyaga MN, Nyagah DM, Njagi A. Pharmaceutical waste: Overview, management, and impact of improper disposal. Med Pharmacol. Available at: https://www.peerscientist.com/volume3/issue2/e1000028/pharmaceutical-waste-overview-management-and-impact-of-improper-disposal.pdf. Accessed on Jul 3, 2024.
[290] T. Honkanen, "Medical waste management in Thailand and Vietnam," Licentiate Master of Tech. Thesis on Sustainability Sciences, LUT School of Energy Systems, Lappeenranta-Lahti University of Technology (LUT), 2024.
[291] Tóth AJ, Gergely F, Mizsey P. Physicochemical treatment of pharmaceutical process wastewater: Distillation and membrane processes. Chem Eng 2011;55:59-67. [CrossRef]
[292] Clarke E, Hottor J. Health care waste management in Ghana-MOH policy and guidelines for health institutions. Available at: https://www.moh.gov.gh/wp-content/uploads/2016/02/Health-Care-Waste-Management-Policy-and-Guidelines.pdf. Accessed on Jul 3, 2024.