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Review

A Review of Grease Trap Waste Management in the US and the Upcycle as Feedstocks for Alternative Diesel Fuels

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Abstract: As byproducts generated by commercial and domestic food-related processes, FOGs (fats, oils, and grease) are the leading cause of sewer pipe blockages in the US and around the world. Grease trap waste (GTW) is a subcategory of FOG currently disposed of as waste, resulting in an economic burden for GTW generators and handlers. This presents a global need for both resource conservation and carbon footprint reduction, particularly through increased waste upcycling. Therefore, it is critical to better understand current GTW handling practices in the context of the urban food–energy–water cycle. This can be accomplished with firsthand data collection, such as onsite visits, phone discussions, and targeted questionnaires. GTW disposal methods were found to be regional and correspond to key geographical locations, with landfill operations mostly practiced in the Midwest regions, incineration mainly in the Northeast and Mid-Atlantic regions, and digestion mainly in the West of the US. Select GTW samples were analyzed to evaluate their potential reuse as low-cost feedstocks for biodiesel or renewable diesel, which are alternatives to petroleum diesel fuels. Various GTW lipid extraction technologies have been reviewed, and more studies were found on converting GTW into biodiesel rather than renewable diesel. The challenges for these two pathways are the high sulfur content in biodiesel and the metal contents in renewable diesel, respectively. GTW lipid extraction technologies should overcome these issues while producing minimum-viable products with higher market values.

Keywords: grease trap waste (GTW); fats, oils, and grease (FOG); biodiesel; renewable diesel; solvent-free lipid extraction

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1. Introduction

FOGs (fats, oils, and grease) are lipid-containing wastes generated from restaurants and food processing facilities, as well as from individual households. These FOG wastes are grossly classified into two categories. The first is used cooking oil (UCO), also called yellow grease, and the second is oil-containing waste from various food production and washing processes. Commercial food service establishments (FSEs) in the US are required to have grease interceptors or grease traps to collect this second type of oil-containing waste, which is also called grease trap waste (GTW). UCO/yellow grease is usually collected and reused in processes that increase its value, such as making biofuels, while GTW is mostly treated as an unusable waste [1].

GTWs have long been problematic for sewer systems, as they are the primary cause (47% in the US) of pipeline blockage and can result in sewer overflows that are very expensive to repair. In Seattle, Washington, between the years of 2003 and 2009, there were 147 sewer backups related to grease blockages. These blockages accounted for one-third of the total incidents in that time period, with an associated cost of approximately USD 220,000 [2]. In San Francisco, California, more than USD 3.5 million was spent on cleaning up GTW clogging and overflow damages [3]. More than 72,000 m^3 (19 million gallons) of sewer overflows were reported in North Carolina from 1998 to September 2001 [4]. In the UK, the "fatberg", a blockage composed of FOG and non-flushable wet wipes, has been consistently reported in sewer systems over the years [5,6]. Frequent sewer overflows have similarly occurred in the US, Hong Kong, Malaysia, Ireland, etc. [7]. In Hong Kong, GTW build-up resulted in more than 60% of sewer blockages in 2000 [8]. Damages from GTWs have been reported in many urban communities around the world on similar scales [9]. An analogy of a heart attack caused by cholesterol can be used to describe the risk that sewer overflows caused by GTWs present to modern sewage systems. Therefore, proper management of GTW is critical for global municipalities in order to solve this problem.

The US EPA has developed a national pretreatment program (EPA 40 CFR 403) to control FOG discharges from commercial FSEs [1]. Most state and local governments have set up FOG regulations that require FSEs to install grease traps or interceptors to separate FOGs from wastewater being discharged to public sewers [10]. FOG regulations require FSEs to properly maintain these traps and usually provide a list of certified grease haulers for services. FSEs are expected to have grease traps periodically cleaned by grease haulers. Some communities also use local municipal codes, such as Seattle SMC 21.16.300, to prohibit FSEs from discharging wastewater that contains more than 100 ppm of FOGs directly into the public sewer system [11]. In accordance with these regulations, FOG generators pay a collection fee to grease haulers, who may either reuse the GTW, dispose of GTW in a landfill, or dispose of GTWs at publicly owned treatment works (POTWs) for a fee. Illegal GTW dumping can occur when haulers try to avoid disposal fees. Such cases have been reported in Akron, Ohio, between 2015 and 2018 [12,13]. This likely occurred when Akron was still developing a FOG program, which is now enforced and is helping to alleviate the issue.

Commercial FSEs also receive education on FOG management from other sources. The National Restaurant Association (NRA) has developed a "Fats, Oils, and Grease Tool Kit" to better educate restaurants on how to manage their FOGs [14]. UCO recycling is encouraged whenever the means to do so are available to FSEs, while pouring down the drain is discouraged. Many municipalities have UCO collection services, such as San Francisco and the District of Columbia, etc.. Some POTWs also offered UCO collection from individuals.

For individual households, oil-containing wastes from food processing tend to be flushed down the drain and into the public sewer system, where they end up in POTWs. A Canadian study reported that up to 60% of GTWs can be attributed to domestic food preparation activities [15]. This type of GTW is called sewer grease. The quality and quantity of household GTWs are affected by individual activities, such as food purchased, cooking, waste disposal, and cleaning [16]. Additionally, sewer grease tends to be of lower quality due to the longer residence time in the pipes.

GTWs entering POTWs are further classified into two categories: trap grease and sewer grease. To avoid mixing GTWs with other waste, some POTWs have a grease-receiving facility for GTWs only. This type of GTW is usually referred to as trap grease. Since GTWs can also come from sewer pipes, some POTWs mix GTWs into the wastewater headwork. When wastewater reaches the primary settling tanks, GTWs are skimmed off as scum and further dewatered before being sent to a landfill [17]. The classifications of different oil-containing byproducts are shown in Figure 1.

The current position of GTWs in urban communities is primarily a waste and economic burden to the stakeholders involved. Because GTWs come from food preparation, cleaning at home, and commercial FSEs, increasing urbanization or urban revitalization will likely increase GTW generation and its associated negative impacts. To resolve this, resource conservation and reuse through landfill diversion and product upcycling can help reduce the carbon footprint and provide other benefits [18]. Instead of being disposed of as waste at a cost, GTWs should be more beneficially incorporated into urban food–energy–water (FEW) systems through repurposing. There are several GTW upcycle pathways, including anaerobic digestion, which have been implemented by stakeholders and are supported by many publications. Based on the waste hierarchy proposed by the European Parliament Council, biodiesel production is preferred as a waste reuse pathway over anaerobic digestion [19]. Interest in upcycling GTWs as feedstocks for biodiesel or renewable diesel is largely motivated by feedstock costs, which typically constitute 70–90% of biodiesel production costs [20]. In addition, converting waste oil feedstocks to alternative diesel fuels (ADFs) results in higher GHG reductions than using virgin feedstocks [21,22]. Under the low-carbon fuel standard (LCFS), which is established in western regions of the US and Canada, GTW-derived biodiesel has one of the lowest carbon intensities, with as high as 86% carbon reduction compared to petroleum diesel [23,24]. As municipalities are striving to lower their carbon footprints, GTW reuse will receive more attention.

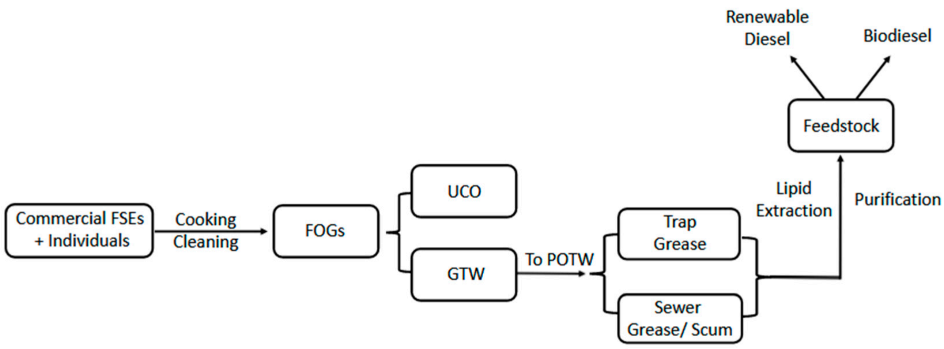

Figure 1. Generation and upcycle of oil-containing byproducts from food preparation processes.

In the US, many municipalities manage GTW through POTWs, but the data are usually not publicly available. Therefore, as depicted in Figure 1, the goal of this paper is to provide a survey of the current GTW management practices of POTWs in the US, as many of the POTWs serve as GTW aggregators. Technologies for GTW upcycling as feedstocks for alternative liquid transportation fuels, both biodiesel and renewable diesel, are also summarized, along with each of their potential challenges. GTW inventory and properties pertinent to these ADFs are also briefly summarized.

2. Current GTW Management in POTWs in the US

Details on GTW collection, handling, and disposal are usually not available on websites or in publications. Therefore, it is necessary to conduct an interview-based survey with as many POTWs as possible. Information on US POTWs was obtained from USEPA's 2012 data dashboard of the Clean Watersheds Needs Survey [25], which contained 14,691 POTWs. Based on this database, the POTWs were first sorted into four categories by the daily processing capacity, MGD (million gallons per day). The treatment capacity of the largest 50 POTWs (top 50) is at least 92 MGD, that of the largest 100 POTWs (top 100) is at least 52 MGD, the largest 1000 POTWs (top 1000) with at least 5.3 MGD and those outside the top 1000.

Select POTWs from the top 1000 (daily processing capacity of more than 5.3 MGD) were first contacted via email to inform them of the purpose of the survey. When the POTWs responded with interest to participate, data collection was performed via onsite visits (preferred), phone calls, or emails with a standard questionnaire on their collection and handling of GTW (see the Supplementary Material). The following technical details were collected: facility capacity, GTW management program, GTW disposal methods, GTW disposal cost, other GTW handling details, and whether they accept GTW from haulers, etc.

Firsthand information on GTW management was obtained from 36 POTWs. Overall, 25 out of the 36 POTWs were visited onsite, with a tour and face-to-face discussion, while data collection from the rest was carried out through phone calls (usually lasting no more than 15 min) and emails. The 36 POTWs were located across 15 states, as well as the District of Columbia (shown in Figure 2). Based on the census regions of the US, sixteen = POTWs are located in the East North Central region; four are located in the New England region, three in the East South Central region, five in the Mountain region, three in the Pacific region, one in the Middle Atlantic region, one in the West North Central region, and three in the South Atlantic region [26].

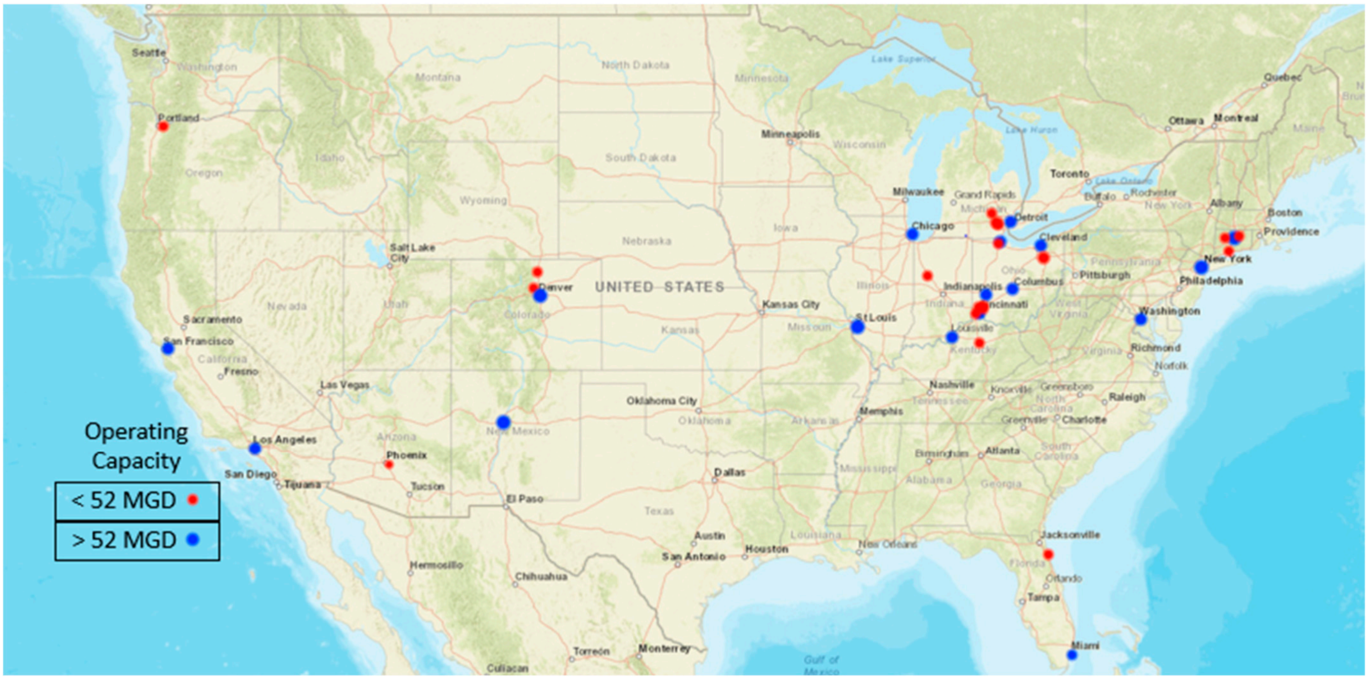

Figure 2. Locations of all publicly owned treatment works (POTWs) interviewed (POTWs in blue are among the 100 largest POTWs).

The average processing capacity surveyed is 110.46 MGD, and 18 of those facilities are among the largest 100 POTWs. Overall, 9 of the surveyed 36 POTWs are among the top 50 in the US based on daily processing capacity, including the 4 largest: Stickney Water Reclamation Plant (Chicago, Illinois), Detroit Water and Sewerage Department (Detroit, Michigan), Blue Plains POTW (Washington, DC), and LA Sanitation District (Los Angeles, California). Three of the POTWs surveyed are outside the top 1000 largest facilities.

In total, 19 out of the 36 POTWs do not accept FOGs from grease haulers and only process sewer grease in their facilities. Furthermore, 34 out of 36 POTWs surveyed have established FOG management programs in their service areas, with only 2 being without such a program. One POTW (in the Pacific region) without such a program plans to manage GTWs as a resource instead of a waste. They also plan to negotiate a bulk GTW collection fee with grease haulers to benefit FSEs in their service area (with the co-benefit of more consistent GTW quality) [27]. The second POTW without such program is located in the Midwest. These two locations only represent 2.41% of the total treatment capacity included in the survey.

POTWs typically dispose of GTW through one or more of the following methods: landfill, incineration, and digestion. The choice of disposal method is largely based on cost, local regulations, and the resources available.

2.1. Landfill

Landfill disposal of GTWs is reported at 19 of the 36 POTWs surveyed, which makes up 65.93% of the total capacity. Moreover, 16 out of the 19 POTWs are from the Midwest (East North Central and East South Central), with the remaining 3 POTWs located in the South Atlantic. This is mainly due to the much lower disposal costs in the Midwest (e.g., USD 15–USD 32/ton) [28,29]. While the low landfill cost may discourage POTWs from investing in GTW reuse technologies, it is important to note that landfill costs are significantly higher (USD 75–USD 95/ton in the state of California and up to USD 260/ton in Connecticut and New York, largely due to regulations and land availability [30]. Additionally, landfill disposal has significant negative environmental impacts, and the landfill diversion of organic wastes has become more commonly practiced as a result.

Two representative cases of POTWs are summarized as follows.

A POTW in southwest Ohio (OHTW), which falls in the largest 50 category, handles approximately 200 million gallons of wastewater per day and has nine treatment plants. Both septic and trap grease are collected from 60 certificated grease haulers at approximately 1.6 million pounds of GTW per year, which are mixed into the primary settling tank along with sewage. Oily contents floating on top of the wastewater are skimmed mechanically and transported into a separator tank for further dewatering [31]. The sewer grease and trap grease mixture are then mixed with other dry wastes for landfill disposal, with an annual operation cost of around USD 208,000 [28]. The process for sewer grease dewatering has improved over time at OHTW, largely by changing from open dumpsters to filter bags (Figure 3). These waste-filled bags are placed in truck-sized dumpsters to be hauled directly to the landfill. This can reduce the volume of disposal as well as the odor. The filter bag method has been adopted by several POTWs.

(**a**) (**b**)

Figure 3. GTW disposal in open dumpsters (**a**) and in filter bags (**b**) at a POTW in southeastern Ohio (OHTW).

A POTW in Northern Kentucky (KYTW) operates three facilities, and we visited the largest one (46.5 MGD) multiple times. KYTW has built a grease-receiving station to accept GTWs from about 30 certified haulers in the area. Unlike the OHTW, KYTW separates GTWs from septic waste at a dedicated grease-receiving station. By separating GTWs as hauler/render's grease and scum (in wastewater), KYTW plans to offer higher-quality GTWs for reuse in the future. The GTWs are sent to a concentration tank to reduce the water content and are later placed into bags for transportation to a landfill. At this time, no reuse market for these GTWs has been developed. Records indicated that they received approximately 354,000 gallons of GTWs in 2019. A similar quantity of GTWs from the sewer pipes, which are skimmed off at the primary clarification tanks, was recorded. The annual landfill cost of GTW disposal at this location was in the range of USD 80,000 to USD 160,000 [29].

2.2. Anaerobic Digestion

In this survey, 8 of 36 POTWs (16.34% by capacity) employed GTW anaerobic digestion. Four POTWs are in the Mountain Region, three are in the Pacific Region, and one is in East North Central Region. Most are located in areas where landfill costs are higher than in the Midwest. GTWs have high organic contents that are desirable for methane production but suffer from several challenges [32]. These challenges include variable GTW availability, a high free fatty acid (FFA) content in the GTW, and contaminants in the biogas (such as hydrogen sulfide) [33–35]. Furthermore, the capital investment and complexity of producing and utilizing methane from anaerobic digestion are also limiting factors [36]. With food waste digestion increasing in recent years, more investment may help overcome the challenges. Two representative cases are described below.

The largest POTW in the State of California operates at 325 MGD and has more than 10,000 food services in its service area. However, the POTW does not accept GTWs from grease haulers. The scum grease is mixed with activated sludge before being added to the digester, which generates combined heat and electricity for the plant [37].

The wastewater authority in New Mexico pilot-tested a GTW receiving station for its 11 POTWs, which all currently have an operational digestion system [33]. Results suggested that high concentrations of FFAs inhibited methane generation, and methane produced from GTW contained corrosive and odorous hydrogen sulfide as a result [34,35].

2.3. Incineration

Our survey indicated that GTW incineration is practiced at seven POTWs (six were onsite visits), which represents 15.32% of the capacity. Five of these POTWs are located in the Northeast (New England and Middle Atlantic) region, with the remaining two in the Midwest (East North Central and West North Central) region. Incinerators are effective in volume reduction (>80%) but require additional fuels to start the process. GTWs are incinerated together with biosolids and can be helpful to the combustion process because of their higher heating values.

The GTWs are mainly from grease haulers without septage mix and are typically further processed via settling, moisture removal (by gravity thickeners or centrifuges), and heating prior to incineration. One of the top 1000 largest POTWs located in the New England area, previously concentrated the GTW received and then sent it out for incineration. Due to increased regulation on phosphate removal and the decommissioning of the outside incinerator in 2023, they redirected the GTW to feed the microbes necessary for phosphate removal. The composition of the GTW they received also changed over time. They receive one truckload of glycerin-containing wastewater every day, while receiving high amounts of trap grease every three months when restaurants clean their kitchens of GTW [38]. Another POTW in the New England area outsourced its incineration operations to a private company. This company sold the processed trap grease to the UK for biodiesel production because of their convenient port location, but this transaction was interrupted by the pandemic [38]. Most of the incinerators in the Northeast are close to their commissioned age, or their permits are nearing their renewal dates, which offers a timely opportunity for GTW reuse.

In recent years, a few POTWs have built or are planning to build grease-receiving stations dedicated to collecting GTWs from grease haulers without septic waste mixing. This could greatly improve the purity of GTWs and facilitate subsequent reuse. For example, KYTW's grease-receiving station, as well as a station at the Northern Ohio POTW, have both been deployed since 2015. This practice is also being considered by several POTWs that have historically not accepted GTWs, such as the POTW in Illinois (one of the largest in the US).

Due to safety reasons, the use of GTWs in human food for consumption is restricted in many parts of the world. In China, the misuse of GTWs (referred to as ditch oil) as counterfeit cooking oil is heavily prosecuted, and FSEs are under constant supervision as a result [19,39]. The use of GTW as animal feed is largely discontinued in the US due to more stringent regulations, particularly the Food Safety Modernization Act.

2.4. Limitations

Based on the USEPA's Clean Watersheds Needs Survey 2012 data dashboard, there are 14,691 POTWs in the United States [25]. This paper included a survey of only 36 POTWs, which seems small with limited geographical coverage of 15 states and the District of Columbia. However, the four largest POTWs were covered in our survey, with nine being in the top 50, eighteen being in the top 100, and three POTWs being outside of the top 1000 of the EPA databases. This suggests that our survey included a diverse population of POTWs at various capacity levels. Our data may be skewed toward larger POTWs, but these locations might be more likely to adopt the GTW upcycle technologies.

3. GTWs as Potential Feedstocks for ADFs

In the US, the transportation sector is now the largest source of carbon emissions, representing 37% of national greenhouse gas (GHG) emissions and surpassing the power sector. Transportation has also become the highest GHG emission source in many urban communities, which means that implementing better methods of decarbonization is critical. Currently, the heavy-duty transportation sector has limited the decarbonization options available. Biodiesel and renewable diesel can provide both a short-term and long-term solution to this rising issue, and incorporating the combined use of these fuels has been increasingly considered by stakeholders [40]. Currently, ADF only constitutes 10.5% of diesel consumption in the US, and there is certainly room to grow.

3.1. Potential Use as Feedstock for Biodiesel

Making biodiesel from UCO or yellow grease is relatively straightforward, largely due to its higher quality [41]. Many biodiesel producers, as well as several laboratories, use a modern two-step process, which includes acid esterification followed by alkaline transesterification [42].

There are many laboratory-scale studies focused on converting trap grease to biodiesel [43–49]. It is also of better quality than the sewer grease described in Tu et al. (2016) [17]. Trap grease lipids are extracted using chemical solvents (hexane, isopropyl alcohol, etc.), either as a single solvent or a mixture. Lipids are then concentrated by removing the solvents and made into biodiesel through a two-step process using homogenous catalysts, which is standard practice in the biodiesel industry [50–52]. Heterogenous catalysts have also been developed to convert GTWs to biodiesel, which mostly occurs in laboratories [9]. In practice, solvent extraction has not been viewed as profitable by the biodiesel industry, largely due to added cost and safety issues [53,54]. In addition, these technologies compete with the biodiesel industry, as they also make biodiesel as the final product.

Trap grease lipids can also be obtained via heating and filtration, which result in brown grease. However, biodiesel produced from brown grease alone does not meet the 15 ppm sulfur specification of ASTM 6751 and cannot be sold commercially [43,55,56]. The lower market value of brown grease (compared to yellow grease) is another economic limitation for commercialization.

Based on the techno-economic status of GTW reuse, a solvent-free lipid extraction process was developed to develop an emulsified sewer grease into yellow grease, with the sulfur content of the resultant biodiesel being within the ASTM 6751 requirement of 15 ppm. The optimum operating conditions reported were 70 °C, 4–6 h, and a UCO-GTW (wt/wt) ratio of 3.6:1 [17]. Another significant advantage of this technology is that it does not require a separate moisture removal process, which can also effectively lower the production cost. This process also increases product value by having yellow grease as the minimum-viable product instead of brown grease and by avoiding competition with the biodiesel industry. This solvent-free extraction technology is especially effective with emulsified sewer grease, as the lipids cannot be obtained via direct heating. This technology also works with trap grease, as indicated in another study [57].

3.2. Potential Use as Feedstock for Renewable Diesel

Although it emerged in the US 10 years later than biodiesel, renewable diesel consumption increased rapidly and reached 2868 million gallons production in 2023, significantly surpassing that of biodiesel, 1939 million gallons. The expansion of renewable diesel is largely related to petroleum companies retrofitting their petroleum facilities for renewable diesel production [58]. By 2031, approximately one billion gallons per year of renewable diesel could be needed in California alone [59].

Overall, 90% of all renewable diesel is produced in the US, and so is 87.6% of biodiesel [60,61]. UCO/yellow grease constitutes about 29.1% of renewable diesel feedstock, while the "other" category has increased to 8.5%, which GTWs can potentially become a part of [21].

In recent years, the oil feedstocks used for biodiesel have increasingly been converted into renewable diesel, which is mainly comprised of hydrocarbons that meet the specifications of diesel fuels. Oils and fats undergo either decarboxylation or hydrodeoxygenation to create renewable diesel with hydrogen and catalysts, such as NiMO/'ϒ-Al_2O_3 [62]. This occurs at ambient pressure with temperature ranges of 300–400 °C. The resultant hydrocarbons have either the same number of carbons as the parent oil/fat (e.g., 18 or 16 as the most common) or one carbon less (17 or 15), depending on the hydro-treating process used [63]. Renewable diesel produced in the US also undergoes isomerization to improve fuel quality, as straight-chain hydrocarbons tend to have higher melting points and cloud points.

A few key differences between biodiesel and renewable diesel are shown in Figure 4. The first major difference is the production method, which results in different compositions for biodiesel and renewable diesel. Renewable diesel is produced via catalytic hydro-processing and is also called hydrodeoxygenation or hydrotreating at much higher temperatures. Biodiesel is composed mainly of methyl esters, while renewable diesel consists of hydrocarbons closer to petroleum diesel. Biodiesel is usually blended into petro-diesel from 7% (called B7 in the EU) to 35% (called B35 in Indonesia), while B20 as the blending rate is commonly acceptable [64]. However, renewable diesel can be added to diesel at any rate. Since hydro-processing tends to be more energy intensive, using biodiesel can result in greater GHG reductions [22]. Higher NOx emissions, or even higher amounts of particulate matter (PM), can be produced with biodiesel combustion but not with renewable diesel [64].

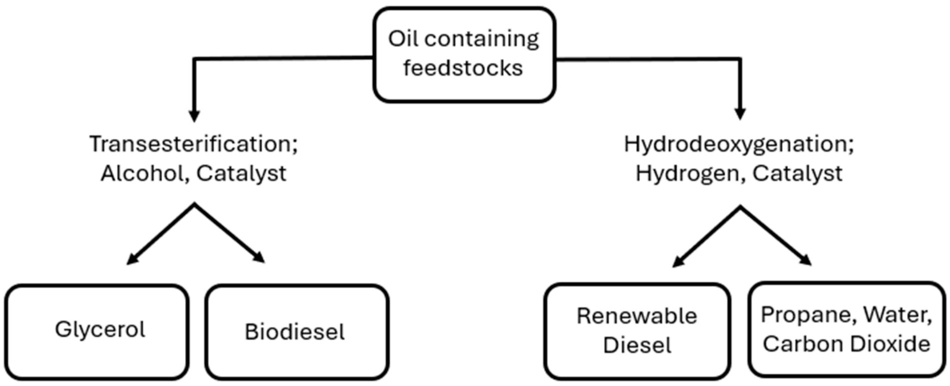

Figure 4. Differences between biodiesel and renewable diesel from oil feedstocks.

Like biodiesel, the cost and quality of feedstock are also essential for renewable diesel production. The sulfur issue relating to GTWs as a biodiesel feedstock seems to be less of an issue for renewable diesel. However, impurities present in GTWs, such as Na, Ca, Mg, and Fe, and non-metals, such as phosphorous and chlorine, may cause catalyst deactivation during hydrodeoxygenation [65].

For either of these ADFs' upcycling, co-location with POTWs may be desirable for multiple reasons. Many POTWs in the US serve as aggregation facilities for GTW. Some are interested in converting GTW to biofuels themselves, while the majority prefer a third party to handle this issue. In both cases, co-location of the GTW lipid extraction process with a POTW can be potentially advantageous. The practice of GTW lipid–solid separation has the potential to produce two types of energy. The lipids can be upcycled as biofuel feedstock, and wet solids can be used for methane production, while the rest can be returned to wastewater treatment plants. Desirable POTWs for co-location include the following: large POTWs that receive large quantities of GTWs from their service areas and facilities designated for GTW receiving and processing, even if their wastewater processing capability might not be large. In Connecticut, GTWs from FSEs are sent to two designated POTWs. Although these POTWs are not on the USEPA's top 100 list, they can be suitable locations for GTW reuse. A third type of co-location can be within large FSEs, which generate significant quantities of GTWs. Onsite GTW upcycling can reduce GTW generation and produce alternative energy. This will also reduce their landfill costs and avoid fines due to excess GTW discharge.

3.3. Repositioning GTW in the Food–Energy–Water Cycles

Currently, GTWs are largely taken out of the FEW cycles as waste, which is neither sustainable nor cost-effective when considering their negative environmental impacts. Proper management and technological innovation are both essential for positively repositioning GTWs in urban FEW cycles, as shown in Figure 5.

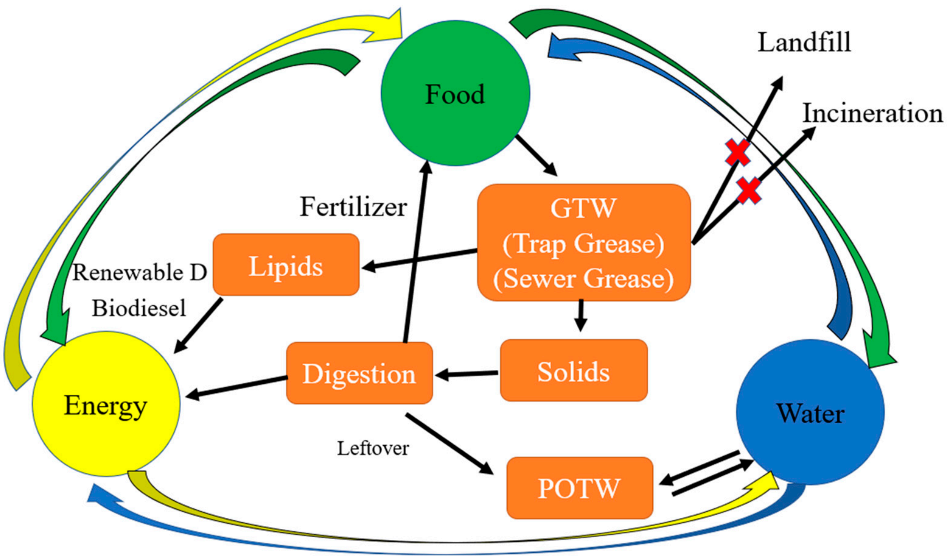

Figure 5. Potential upcycle pathways of GTW in urban food–energy–water systems.

The lipids in GTWs can be converted to ADF, and the wet solids can be digested or used as bio-methane, meaning both can replace fossil fuel energy. This is consistent with a study indicating that the dual fuel approach of using lipids as biodiesel and leftover solids for methane production better reduces energy consumption and GHG emissions [66]. Byproducts from digestors can be used as fertilizers (e.g., to support urban farming).

4. GTW Inventory and Properties as Alternative Diesel Fuels (ADFs)

4.1. A Brief Inventory of GTW and UCO in the US

In order to better manage GTWs, it is essential to obtain location-specific GTW generation rates. However, data from private companies (grease haulers) are considered proprietary, and data from POTWs are also usually not available to the public. Based on a study of 30+ metropolitan areas in the US in 1998, the average trap grease generation per area was about 6.06 kg/yr (13.37 lbs/yr) and 1.81 billion kilograms annually [67]. This rate is still used by many metropolitan areas to estimate FOG generation due to the lack of data. However, a few regional studies reported much smaller FOG inventories compared to the national average. A GTW generation rate of 2.85 kg/person/yr was reported for Wake County, North Carolina [68]. A rate of 0.77 kg/person/yr was reported for Columbia, South Carolina [69]. A rate of 3.75 kg/person/yr was reported for the Cincinnati, Ohio, area [68]. In the UK, a 0.8 kg/yr per capita GTW generation was reported [70].

4.2. GTW Properties Relevant to Upcycle as ADF Feedstocks

'Raw' grease trap waste is usually a mixture of lipids, water, and solids and contains a 2–10% lipid content. The GTWs are usually further concentrated in POTWs to reduce the volume of water before disposal. Samples from two POTWs were analyzed to better understand the properties related to upcycling as ADFs.

The first sample is sewer grease (SG) collected from OHTW, which is scum grease collected from the primary settling tank after being placed in large canvas bags and dried for approximately 8 h. The second sample is trap grease (TG) collected from a POTW in Northern Kentucky (KYTW). The SG underwent solvent extraction for the lipid content, was filtered to determine solid content, and was dried to reduce moisture. Heating and filtration were used to determine the lipid content of TP [57].

GTW compositions are shown in Table 1, which varies over time due to different food-processing operations. The moisture of SG was significantly reduced from 58% to below 40% due to the change in SG drying [17]. Since the summer of 2016, the measured properties have tended to be relatively stable over the seasons and years. The higher lipid contents of both samples during the winter are likely related to increased cooking during the November/December holiday season. Due to the high temperature and hydrolysis, the lipids in GTWs tend to be mainly in the form of FFA instead of triglycerides. The FFA content varies significantly among different GTWs.

Table 1. Compositions of sewer grease (SG) and trap grease (TG) wastes (GTWs) over time.

	Time Period	Moisture, wt%	Lipid Content, wt%	Solids, wt%
Sewer Grease	Prior to 2016	58.9	22.9	18.2
	Summer 2016	37.81	30.50	31.69
	Winter 2017	39.62	29.8	30.58
	Fall 2019	39.60	30.85	29.55
	Winter 2020	33.51	32.22	34.27
Trap Grease	Winter 2017	53.81	23.35	22.34
	Fall 2019	51.04	32.00	18.69
	Winter 2020	42.66	49.01	8.33

The high heating value (HHV) of the two samples was in the range of 29.3–34.0 MJ/kg, which is at the lower range of 32.9–39.4 MJ/kg reported [9]. These values are comparable to those of coal, being that anthracite is 30.08 MJ/kg, and bituminous coal is between 18.8 and 29.3 MJ/kg. However, the values were lower than those of virgin oils at 39 MJ/kg. The LHV of the two samples was 18.3–23.7 MJ/kg, slightly lower than the 24.5–41.6 MJ/kg reported from the UK [70].

The carbon-to-nitrogen ratios (C/N) were derived from elemental analysis performed by a commercial laboratory (OKI Laboratory, Cincinnati, Ohio) to evaluate the reuse potential of the solids. The desired C/N ratio for anaerobic digestion ranges from approximately 20:1 to 30:1 [71,72]. Both the raw GTW and the wet solids are largely within that range (Table 2), indicating that the remaining solids after lipid extraction are also suitable for anaerobic digestion. Digesting GTW with the lipids removed can be more advantageous, as this can overcome FFA inhibition [66,73].

The metal contents of two grease samples were measured to evaluate their feasibility as feedstocks for renewable diesel. The grease samples were digested, and the metal content was analyzed with flame atomic absorption spectroscopy, as shown in Table 3. This analysis was performed using a PerkinElmer PinAAcle 500 Spectrometer. The much higher calcium content of the sewer grease is likely due to calcium soap formation in the pipes [74], while the iron and copper levels of the trap grease were much higher. Another study reported Ca ranges from 0.2 to 4.2 wt%, Fe from 0.01 to 4%, and Na around 0.004% [9]. More information on the components affecting catalyst deactivation and more measurements of GTW's metal contents are needed to incorporate GTWs as renewable diesel feedstocks.

Table 2. Elemental analysis of sewer grease (SG), trap grease (TG), and wet solids (wt%).

	wt%	C	H	O	N	C/N Ratio
Sewer Grease—Summer 2016	SG	69.32	10.95	19.35	3.28	24.66
	Solids	69.25	10.02	18.64	3.02	26.75
Sewer Grease—Winter 2017	SG	67.83	9.74	19.63	2.65	29.86
	Solids	68.19	10.38	20.88	2.41	33.01
Trap Grease—Winter 2017	TG	69.17	10.12	17.23	3.15	25.62
	Solids	70.36	10.53	16.32	2.79	29.42

Table 3. Metal concentrations (μg/g) of select grease trap wastes (GTWs).

	Na	Ca	Mg	Fe	Cu
Sewer Grease	371.15	6867.28	141.50	513.35	124.02
Trap Grease	408.91	1420.33	254.96	531.78	15.95

4.3. UCO/Yellow Grease Inventory

As part of the FOG, UCO is oftentimes generated together with GTWs. Also, UCO management tends to be closely related to that of GTW.

Preliminary research on UCO collectors around the United States was conducted. Out of the 42 UCO-collecting companies surveyed, 24 (57.1%) of them also provide grease trap cleaning services, indicating they may also be grease haulers. Four of these are also fresh cooking oil providers who offer a turnkey process to take back used oil. Only seven UCO collectors have nationwide operations, which is about 16.7%. This is consistent with GTW haulers, as many are small in scale, usually operating either locally or regionally.

In the US, the UCO collection in 2022 was approximately 0.85 billion gallons, with a global supply of 3.7 billion gallons. The average UCO generation in the US is about 2.5 gallons per person in 2022 and is expected to reach nearly 3.2 gallons per capita in 2030, with 1.1 billion gallons in supply. The fastest-growing markets are in Asia and Latin America, likely due to the high development rates [75].

Overall, 80% of UCO already goes toward the biofuels sector, and the price of UCO has experienced an upward trend over the years. With the need to reduce carbon footprints, low-carbon-intensity UCO is in higher demand in the US, especially where the LCFS is implemented. The cost of UCO depends on whether or not it can be sold as yellow grease or brown grease. Yellow grease contains less than 15% of FFA and less than 2% of moisture, while the FFA content of brown grease is usually greater than 15%. GTWs can be processed into brown grease, while most UCOs are likely sold as yellow grease with a much higher market value [17].

Actual UCO prices can be very different from what is reported. For example, although the reported UCO price is between USD 0.29 and USD 0.30/lb in California, prices of USD 0.45–USD 0.51/lb are still in effect in some New England areas [76,77]. Brown grease was only worth USD 0.05/lb in 2016, while yellow grease was USD 0.21/lb. The market value of brown grease remained at USD 0.05/lb and was increasing slightly to USD 0.10–USD 0.30/lb until recently [77].

5. Conclusions

This paper provided firsthand information on current GTW management at POTWs around the US through interview-based data collection. The survey indicated a geographical variation in GTW reuse and treatment. Landfill disposal is mostly used in the Midwest region of the US. Incineration is mainly practiced in the Northeast and Mid-Atlantic regions, while anaerobic digestion is mainly used in the West to produce methane and fertilizers for land application. As for GTW disposal practices, both GTW incineration and landfill disposal take away potential resources from the FEW cycles and should be aimed toward recovering useful portions. In addition to energy recovery and carbon footprint reduction, landfill diversion can also save tipping fees and land space.

GTW management presents a global challenge. Various technologies have been developed to convert GTWs into alternative diesel fuels, i.e., biodiesel and renewable diesel. More research has been conducted on converting GTW to biodiesel rather than renewable diesel. The challenge of upcycling GTW as biodiesel feedstock is the sulfur content. The resultant biodiesel must meet the <15 ppm sulfur requirement of the ASTM D 6751 biodiesel standard. The challenge of upcycling GTW as a renewable diesel feedstock is to reduce select heavy metals, which may negatively affect the hydrodeoxygenation process. GTW lipid extraction technologies should overcome these limitations while striving for a minimum-viable product with higher market values. The incorporation of GTW as feedstocks of alternative diesel fuels will be beneficial to municipalities in terms of waste minimization and carbon footprint reduction.

6. Future Directions

For the large-scale adoption of these GTW upcycle technologies, it is essential to comprehensively evaluate the processes in detail through systematic approaches, such as life cycle analysis and technical, economic analysis [78], which were not discussed in this paper. GTW quantities may be limited to the boundaries of municipalities, and the management practices are highly dependent on regulations, policy incentives of the communities, as well as public awareness. These factors should also be taken into considerations in order to better upcycle grease trap waste as value added products.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments11080159/s1, Table S1, Questionnaire to POTWs.

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References

1. US EPA (Environmental Protection Agency). 40 CFR 403 National Pretreatment Program. 2012. Available online: https://www3.epa.gov/npdes/pubs/pretreatment_foodservice_fs.pdf (accessed on 10 June 2024).
2. Gutierrez, S. Seattle's Sewers Are Getting Clogged with Grease. Seattlep. 2011. Available online: http://www.seattlepi.com/local/article/Seattle-s-sewers-are-getting-clogged-with-grease-891503.php. (accessed on 26 May 2024).
3. San Francisco Water, Power, and Sewer (SFWPS). Brown Grease to Biodiesel Demonstration Project. 2011. Available online: http://www.sfwater.org/modules/showdocument (accessed on 12 June 2024).
4. University of North Carolina. In a FOG: Wastewater System Managers Struggle with Fat, Oil, and Grease. Water Resources Research Institute News. 2012, Number 335. Available online: https://repository.lib.ncsu.edu/server/api/core/bitstreams/ce4c0b26-0cfe-4220-af8a-2eaa0ff094fd/content (accessed on 14 June 2024).

5. Moss, S. Don't Feed the Fatberg! What a Slice of Oily Sewage Says about Modern Life. The Guardian: Waste. 2018. Available online: https://www.theguardian.com/environment/2018/feb/18/dont-feed-fatberg-museum-london-clogging-sewers-oil (accessed on 16 June 2024).
6. Blanc, J.; Arthur, S. Management and Recovery of FOG (Fats, Oils, and Greases). Centre of Expertise for Waters. 2013. Available online: https://www.crew.ac.uk/sites/www.crew.ac.uk/files/sites/default/files/publication/CREW_FOG.pdf (accessed on 11 June 2024).
7. Husain, I.A.F.; Alkhatib, M.F.; Jami, M.S.; Mirghani, M.E.S.; Bin Zainudin, Z.; Hoda, A. Problems, control, and treatment of fat, oil, and grease (FOG): A review. *J. Oleo Sci.* **2014**, *63*, 747–752. [CrossRef] [PubMed]
8. Chan, H. Removal and recycling of pollutants from Hong Kong restaurant wastewaters. *Bioresour. Technol.* **2010**, *101*, 6859–6867. [CrossRef] [PubMed]
9. Abomohra, A.; Elsayed, M.; Esakkimuthu, S.; El-Sheekh, M.; Hanelt, D. Potential of fat, oil and grease (FOG) for biodiesel production: A critical review on the recent progress and future perspectives. *Prog. Energy Combust. Sci.* **2020**, *81*, 100868. [CrossRef]
10. National Restaurant Association. Fats Oils Greases. 2024. Available online: https://conserve.restaurant.org/Best-Practices/FOG (accessed on 11 June 2024).
11. Seattle Municipal Code: 21.16.300. 2020. Available online: https://www.seattle.gov/utilities/protecting-our-environment/sustainability-tips/fats-oils-and-grease-(fog)/fog-commercial-kitchens#:~:text=Seattle%20Municipal%20Code%20prohibits%20the%20discharge%20of%20wastewater,from%20their%20private%20sewer%20line%20(SMC%2021.16.300%20B) (accessed on 10 June 2024).
12. Ferrise, A. Akron Officials Ask for Help Tracking Down Illegal Dumping of Grease into Sewer. Cleveland.com. 2015. Available online: https://www.cleveland.com/akron/2015/05/akron_officials_ask_for_help_t.html (accessed on 10 June 2024).
13. Conn, J. Akron Asks for Public's Help after Illegal, Mass Grease Dumping Clogs Pipes at Water Reclamation Plant. Cleveland.com. 2018. Available online: https://www.cleveland.com/akron/2018/03/akron_asks_residents_businesse.html (accessed on 16 June 2024).
14. National Restaurant Association. National Restaurant Association Arms Members with Toolkit on Fats Oils and Grease FOG Control. Vending Times. 2017. Available online: https://www.vendingtimes.com/news/national-restaurant-association-arms-members-with-toolkit-on-fats-oils-and-grease-fog-control/ (accessed on 16 June 2024).
15. Capital Regional District. Fats, Oils and Greases. 2024. Available online: https://www.crd.bc.ca/education/stormwater-wastewater-septic/at-home/protecting-plumbing-treatment/fats-oils-and-grease (accessed on 16 June 2024).
16. Foden, M.; Browne, A.L.; Evans, D.M.; Sharp, L.; Watson, M. The water–energy–food nexus at home: New opportunities for policy interventions in household sustainability. *Geogr. J. 2019 185*, 406–418. [CrossRef]
17. Tu, Q.; Wang, J.; Lu, M.; Brougham, A.; Lu, T. A solvent-free approach to extract the lipid fraction from sewer grease for biodiesel production. *Waste Manag.* **2016**, *54*, 126–130. [CrossRef] [PubMed]
18. Machell, J.; Prior, K.; Allan, R.; Andresen, J.M. The water energy food nexus-challenges and emerging solutions. *Environ. Sci. Water Res. Technol.* **2015**, *1*, 15–16. [CrossRef]
19. Wallace, T.; Gibbons, D.; O'Dwyer, M.; Curran, T.P. International evolution of fat, oil and grease (FOG) waste management—A review. *J. Environ. Manag.* **2017**, *187*, 424–435. [CrossRef] [PubMed]
20. Haas, M.; Foglia, T. Alternate Feedstocks and Technologies for Biodiesel Production. In *The Biodiesel Handbook*, 2nd ed.; Gerhard Knothe, G., Krahl, J., Gerpen, J., Eds.; AOCS Publishing: Urbana, IL, USA, 2005. Available online: https://doi-org.uc.idm.oclc.org/10.1016/B978-1-893997-62-2.50001-2 (accessed on 12 June 2024).
21. Gerveni, M.; Hubbs, T.; Irwin, S. Renewable Diesel Feedstock Trends over 2011–2022. *Farmdoc Dly.* **2023**, *13*, 231. Available online: https://farmdocdaily.illinois.edu/wp-content/uploads/2023/12/fdd122023.pdf (accessed on 12 June 2024).
22. Xu, H.; Ou, L.; Li, Y.; Hawkins, T.; Wang, M. Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States. *Environ. Sci. Technol.* **2022**, *56*, 7512–7521. [CrossRef]
23. Farrell, A.E.; Sperling, D.; Arons, S.M.; Brandt, A.R.; Delucchi, M.A.; Eggert, A.; Farrell, A.E.; Haya, B.K.; Hughes, J.; Jenkins, B.M.; et al. A Low-Carbon Fuel Standard for California Part 1: Technical Analysis. UC Berkeley: Transportation Sustainability Research Center, 2007. Available online: https://escholarship.org/uc/item/8zm8d3wj (accessed on 12 June 2024).
24. California Air Resources Board. LCFS Data Dashboard. 2024. Available online: https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard (accessed on 12 June 2024).
25. US EPA. Clean Watersheds Needs Survey 2012 Report to Congress. 2016. Available online: https://www.epa.gov/cwns/clean-watersheds-needs-survey-cwns-2012-report-and-data (accessed on 16 June 2024).
26. National Centers for Environmental Information. Geographical Reference Maps: U.S. Census Divisions. Climate Monitoring; 2024. Available online: https://www.ncei.noaa.gov/access/monitoring/reference-maps/us-census-divisions (accessed on 11 July 2024).
27. McNeil, D. Resource Recovery Cooperatives for the Security of Consistent Quality Co-Digestion Feedstock. In Proceedings of the WEF Residuals and Biosolids Conference, Seattle, WA, USA, 8–11 April 2017. Available online: https://www.accesswater.org/publications/proceedings/-279717/resource-recovery-cooperatives-for-the-security-of-consistent-quality-codigestion-feedstock?pdfdownload=true (accessed on 12 June 2024).
28. Scanlan, L. (Metropolitan Sewer District of Greater Cincinnati, Cincinnati, OH, USA). Personal communication, 2016.
29. Crawford, J. (Sanitary District No. 1 in Northern Kentucky, Fort Wright, KY, USA). Personal communication, 2020.

30. Las Angeles County Sanitation Districts. Tipping Fees for Solid Waste and Recyclables. 2024. Available online: https://www.lacsd.org/services/solid-waste/tipping-fees-for-solid-waste-and-recyclables#:~:text=-California%20Integrated%20Solid%20Waste%20Management,Management%20Fee:%20$1.50%20per%20ton. (accessed on 16 June 2024).
31. Tu, Q.; Wang, J.; Lu, M.; Chai, M.; Lu, T. Feasibility and Practices of Making Biodiesel Out of Low-Quality Greases. *EM Mag.* **2012**, 26–29. Available online: https://www.researchgate.net/publication/289723044_Feasibility_and_practices_of_making_biodiesel_out_of_low-quality_greases (accessed on 12 June 2024).
32. Long, J.H.; Aziz, T.N.; Reyes, F.L.D.L.; Ducoste, J.J. Anaerobic co-digestion of fat, oil, and grease (FOG): A review of gas production and process limitations. *Process Saf. Environ. Prot.* **2012**, *90*, 231–245. [CrossRef]
33. Gupta, R.; Meacham, D.L.; Parkins, P.; Peacock, T.A.; Montoya, A.L. Lifting the Fog from FOG Receiving. *Proc. Water Environ. Fed.* **2016**, 2167–2185. [CrossRef]
34. Cantrell, K.; Ro, K.; Mahajan, D.; Anjom, M.; Hunt, P.G. Role of thermochemical conversion in livestock waste-to-energy treatments: Obstacles and opportunities. *Ind. Eng. Chem. Res.* **2007**, 8918–8927. [CrossRef]
35. Ryckebosch, E.; Drouillon, M.; Vervaeren, H. Techniques for transformation of biogas to biomethane. *Biomass Bioenergy* **2011**, *35*, 1633–1645. [CrossRef]
36. Seiple, T.E.; Coleman, A.M.; Skaggs, R.L. Municipal wastewater sludge as a sustainable bioresource in the United States. *J. Environ. Manag.* **2017**, *197*, 673–680. [CrossRef] [PubMed]
37. Xu, D. (LA Sanitation District, Los Angeles, CA, USA). Personal communication, 2016.
38. Watkins, D. (Torrington Water Pollution Control Facility, Torrington, CT, USA). Personal communication, 2022.
39. Lu, M.; Tu, Q.; Jin, Y. The gutter oil issue in China. *Proc. Inst. Civ. Eng. Waste Resour. Manag.* **2013**, *166*, 142–149. [CrossRef]
40. Aryanpur, V.; Rogan, F. Decarbonizing Road freight transport: The role of zero-emission trucks and intangible costs. *Sci. Rep.* **2024**, *14*, 2113. [CrossRef] [PubMed]
41. Agnew, R.; Chai, M.; Lu, M.; Dendramis, N. Making biodiesel from recycled cooking oil generated in campus dining facilities. *Sustain. J. Rec.* **2009**, *2*, 303–307. [CrossRef]
42. Chai, M.; Tu, Q.; Yang, J.; Lu, M. Esterification pretreatment of free fatty acid in biodiesel production, from laboratory to industry. *Fuel Process. Technol.* **2014**, *125*, 106–113. [CrossRef]
43. Chakrabarti, A.R.; Hake, J.M.; Zarchi, I.; Gray, D.M.D. Waste Grease Biodiesel Production at a Wastewater Treatment Plant. *Proc. Water Environ. Fed.* **2008**, *14*, 2770–2789. [CrossRef]
44. Wang, Z.M.; Lee, J.S.; Park, J.Y.; Wu, C.Z.; Yuan, Z.H. Optimization of biodiesel production from trap grease via acid catalysis. *Korean J. Chem. Eng.* **2008**, *25*, 670–674. [CrossRef]
45. Jolis, D.; Loiacono, J.; Kwan, L.; Sierra, N.; Ving, K.; Martis, M. Co-location of brown grease to biodiesel production facility at the oceanside wastewater treatment plant in San Francisco, CA. *Proc. Water Environ. Fed.* **2010**, *9*, 6816–6829. [CrossRef]
46. Ngo, H.L.; Xie, Z.G.; Kasprzyk, S.; Haas, M.; Lin, W.B. Catalytic synthesis of fatty acid methyl esters from extremely low quality greases. *J. Am. Oil Chem. Soc.* **2011**, *88*, 1417–1424. [CrossRef]
47. Turner, N.B.; Landsburg, E.B.; Feldman, E.; Varghese, A.R.; Blaza, G. Beneficial reuses of sewer grease: Biodiesel production vs. anaerobic digestion. In Proceedings of the Air & Waste Management Association 104th Annual Conference, Orlando, FL, USA, 21–24 June 2011; Paper 2011-A-627-AWMA.
48. Watson, E.G. Frying up Energy Independence—The Feasibility of Fats, Oils and Greases (FOG)-Derived Biofuel Production. *Fla. Water Resour. J.* **2011**. Available online: http://www.fwrj.com/techarticles/0611%20tech1.pdf (accessed on 16 June 2024).
49. Noshadi, I.; Kanjilal, B.; Du, S.; Bollas, G.M.; Suib, S.L.; Provatas, A.; Liu, F.; Parnas, R.S. Catalyzed production of biodiesel and bio-chemicals from brown grease using ionic liquid functionalized ordered mesoporous polymer. *Appl. Energy* **2014**, *129*, 112–122. [CrossRef]
50. Yuttachana, N. Feasibility Study on Quantity and Fuel Properties of Extracted Lipid from Trap Grease Waste. Master's Thesis, Mahidol University at Thailand, Nakhon Pathom, Thailand, 2006.
51. Mondala, A.; Liang, K.; Toghiani, H.; Hernandez, R.; French, T. Biodiesel production by in situ transesterification of municipal primary and secondary sludges. *Bioresour. Technol.* **2009**, *100*, 1203–1210. [CrossRef] [PubMed]
52. Pokoo-Aikins, G.; Heath, A.; Mentzer, R.A.; Mannan, M.S.; Rogers, W.J.; El-Halwagi, M.M. A multi-criteria approach to screening alternatives for converting sewage sludge to biodiesel. *J. Loss Prev. Process. Ind.* **2010**, *23*, 412–420. [CrossRef]
53. Siddiquee, M.N.; Rohani, S. Lipid extraction and biodiesel production from municipal sewage sludges: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1067–1072. [CrossRef]
54. Voegele, R. A Critical Component. Biodiesel Magazine. 2012. Available online: https://biodieselmagazine.com/articles/a-critical-component-8295, (accessed on 11 June 2024).
55. Cairncross, R.A.; Olson, M.; Spatari, S. Extracting Lipids from Wastewater to Produce Biofuels. WE&RF Project Report. 2016. Available online: https://www.waterrf.org/research/projects/extraction-lipids-wastewater-produce-biofuels-0 (accessed on 16 June 2024).
56. URS Corporation. *Wastewater Sector State of the Industry Report: Conversion of Brown Grease to Biofuel*; URS Corporation: San Francisco, CA, USA, 2010.
57. Zhang, J. Utilization of Fats, Oils and Grease in Biodiesel Production: From Market Study to Technical Feasibility. Master's Thesis, University of Cincinnati, Cincinnati, OH, USA, 2017. Available online: https://etd.ohiolink.edu/acprod/odb_etd/etd/r/1501/10?clear=10&p10_accession_num=ucin1511801164066707 (accessed on 16 June 2024).

58. Mata, A.; Hughes, E.; Lu, M. Fats, Oils and Grease (FOGs) as a Potential Feedstock for Renewable Diesel. *AWMA Mag. Environ. Manag.* **2021**, 35–37. Available online: https://www.awma.org/emmay21 (accessed on 16 June 2024).
59. Leonard, J.; Couch, P. The Potential and Challenges of Renewable Diesel Fuel for Heavy-Duty Vehicles. Advanced Clean Tech News. 2017. Available online: https://www.act-news.com/news/the-potential-and-challenges-of-renewable-diesel-fuel-for-heavy-duty-vehicles/ (accessed on 16 June 2024).
60. U.S. EIA. Table 10.4a: Biodiesel Overview. *EIA Mon. Energy Rev.* **2024**, *1*, 194. Available online: https://www.eia.gov/totalenergy/data/monthly/pdf/sec10_8.pdf (accessed on 10 June 2024).
61. U.S. EIA. Table 10.4b: Renewable Deisel Fuel Overview. *EIA Mon. Energy Rev.* **2024**, *1*, 195. Available online: https://www.eia.gov/totalenergy/data/monthly/pdf/sec10_9.pdf (accessed on 10 June 2024).
62. Knothe, G. Biodiesel and renewable diesel: A comparison. *Prog. Energy Combust. Sci.* **2010**, *36*, 364–373. [CrossRef]
63. Smagala, T.G.; Christensen, E.; Christison, K.M.; Mohler, R.E.; Gjersing, E.; Mccormick, R.L. Hydrocarbon Renewable and Synthetic Diesel Fuel Blendstocks: Composition and Properties. *Energy Fuels* **2013**, *27*, 237–246. [CrossRef]
64. Lu, M.; Tzillah, A.; Chai, M.; Aloraimi, O. Compositional Analysis of Biodiesel Particulate Matter (BPM) from a Non-Road Diesel Generator. *Energies* **2023**, *16*, 5010. [CrossRef]
65. Arora, P.; Ojagh, H.; Woo, J.; Lind Grennfelt, E.; Olsson, L.; Creaser, D. Investigating the effect of Fe as a poison for catalytic HDO over sulfide NiMo alumina catalysts. *Appl. Catal. B Env.* **2018**, *227*, 240–251. [CrossRef]
66. Tu, Q.; McDonnell, B.E. Monte Carlo analysis of life cycle energy consumption and greenhouse gas (GHG) emission for biodiesel production from trap grease. *J. Clean. Prod.* **2016**, *112*, 2674–2683. [CrossRef]
67. Wiltsee, G. Urban Waste Grease Resource Assessment. National Renewable Energy Laboratory, 1998. Available online: https://www.nrel.gov/docs/fy99osti/26141.pdf (accessed on 12 June 2024).
68. Wang, J. Feasibility Study for a Community scale Conversion of Trap Grease to Biodiesel. Master's Thesis, University of Cincinnati, Cincinnati, OH, USA, 2012. Available online: https://etd.ohiolink.edu/acprod/odb_etd/ws/send_file/send?accession=ucin1330024170&disposition=attachment (accessed on 21 July 2024).
69. Chesebrough, E.G. From GREASE traps to Bio-Gold? An Environmental and Economic Cost-Benefit Assessment of Converting Trap Grease to Biodiesel. Master's Thesis, University of South Carolina at Columbia, Columbia, SC, USA, 2008.
70. Collin, T.; Cunningham, R.; Deb, M.; Villa, R.; MacAdam, J.; Jefferson, B. Energy potential of household fats, oils and grease (FOG) waste. *Water Environ. J.* **2022**, *36*, 132–141. [CrossRef]
71. Wan, C.; Zhou, Q.; Fu, G.; Li, Y. Semi-continuous anaerobic co-digestion of thickened waste activated sludge and fat, oil and grease. *Waste Manag.* **2011**, *31*, 1752–1758. [CrossRef] [PubMed]
72. Kamperidou, V.; Terzopoulou, P. Anaerobic Digestion of Lignocellulosic Waste Materials. *Sustainability* **2021**, *13*, 12810. [CrossRef]
73. Salama, E.-S.; Saha, S.; Kurade, M.B.; Dev, S.; Chang, S.W.; Jeon, B.-H. Recent trends in anaerobic co-digestion: Fat, oil, and grease (FOG) for enhanced biomethanation. *Prog. Energy Combust. Sci.* **2019**, *70*, 22–42. [CrossRef]
74. He, X.; Iasmin, M.; Dean, L.O.; Lappi, S.E.; Ducoste, J.J.; de los Reyes, F.L., 3rd. Evidence for fat, oil, and grease (FOG) deposit formation mechanisms in sewer lines. *Environ. Sci. Technol.* **2011**, *45*, 4385–4391. [CrossRef]
75. GlobalData. Global Supply and Trade of Used Cooking Oil. UCO Supply Outlook. 2023. Available online: https://cleanfuels.org/wp-content/uploads/GlobalData_UCO-Supply-Outlook_Sep2023.pdf (accessed on 16 June 2024).
76. USDA. National Weekly Ag Energy Round-Up. Agricultural Marketing Service; 2024. Available online: https://www.ams.usda.gov/mnreports/lswagenergy.pdf (accessed on 16 June 2024).
77. Chai, M. (American Green Fuels, New Haven, CT, USA). Personal communication, 2024.
78. Osman, A.; Fang, B.; Zhang, Y.; Liu, Y.; Yu, J.; Farghali, M.; Rashwan, A.; Chen, Z.; Ihara, I.; Rooney, D.; et al. Life cycle assessment and techno-economic analysis of sustainable bioenergy production: A review. *Environ. Chem. Lett.* **2024**, *22*, 1115–1154. [CrossRef]

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