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Case Report

# Mandatory Recycling of Waste Cooking Oil from Residential and Commercial Sectors in Taiwan

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**Abstract:** Waste cooking oil (WCO) has been considered a low-cost and renewable feedstock for the production of biodiesel and biobased products if it can be economically and efficiently collected and recycled. The objective of this case study is to review the scientific background of WCO recycling in the literature in connection with the regulatory and promotional measures in Taiwan under the authorization of a legal waste management system. Furthermore, the updated information about the on-line reporting WCO amounts in Taiwan is also analyzed to illustrate its significant increase in the recycling status of WCO officially designated as one of the mandatory recyclable wastes since 2015. Finally, an overview of available utilization of WCO as biodiesel, fuel oil, and non-fuel related uses is briefly addressed in this paper. It shows that the collected amounts of WCO from residential and commercial sectors in Taiwan significantly increased from 1599 tonnes in 2015 to 12,591 tonnes, reflecting on the WCO recycling regulation effective since 2015. Practically, the most important option for this urban mining is to reuse WCO as an energy source for the productions of biodiesel and auxiliary fuel. Other non-fuel related uses include the production of soaps/detergents, C-18 fatty acids, and lubricants. However, the reuse of WCO as a feed additive should be banned to prevent it from re-entering the food chain.

**Keywords:** waste cooking oil; recycling; biodiesel; non-fuel use; regulatory promotion; circular economy

## 1. Introduction

With population and living level on the increase, it has led to a higher demand of edible oils because they provide essential nutrients and energy for everyone's activities required. Edible oils mostly consist of triacylglycerides (more than 95%), which are composed of different fatty acids [1]. Other compounds or groups of compounds, including free fatty acids, phospholipids, phytosterols, tocopherols, and other antioxidants, are also found in plant oils or animal fats. The so-called waste cooking oil (WCO) contains many harmful substances, thus causing health hazards when people consume it or its processing products. Unfortunately, an incident of "food safety scandal" happened in Taiwan in September 2014 [2]. In this food scandal, some lard/lard products manufactured by a Taiwanese company might have been contaminated, as they were produced from collected waste oils and/or lard for animal feed. On the other hand, WCO could cause some environmental pollution if it is illegally disposed of, such as malodor, water pollution, and vapor explosion. More noticeably, WCO represents a renewable resource for the production of fuel oils and alternative feedstocks in replacements of petroleum-based chemicals [3].

Basically, WCO is generated from the cooking process for human daily consumption. Its source may be derived from households and commercial activities. Due to its chemical features, recycling of WCO not only provides a renewable feedstock for producing biofuels (e.g., biodiesel) and biobased products, but also mitigates greenhouse gas (GHG) emissions and avoids environmental pollution arising from its improper handling (e.g., disposed of at a sanitary landfill). In addition, the reuse of

WCO as energy sources and non-food uses can prevent it from re-entering the food chain. In order to promote the recycling of underutilized WCO from municipal solid waste (MSW), the central competent authority (i.e., Environmental Protection Administration, EPA) in Taiwan promulgated the WCO recycling system under authorization of the Waste Management Act since 2015. Among these regulatory measures, WCO was first listed as one of mandatory recyclable wastes based on its potential for recycling and reuse. Subsequently, the WCO recycling system can be integrated into the 4-in-1 Recycling Program, which has been promulgated since 1997 [4,5]. Herein, the Program includes community residents, private sector (collectors and recyclers), local governments (municipal collection teams), and recycling fund. On the other hand, the EPA further listed the major generation sources, including fast food chain outlets, restaurants, food manufacturers and hotels, which are required to submit its on-line report for tracking WCO management.

In the previous paper [6], the energy utilization from WCO for the biodiesel production in Taiwan has been reviewed and discussed. More significantly, there are no case reports to date that detail the regulatory and promotional measures for mandatory recycling of WCO from the residential and commercial sectors in the literature. First of all, the objective of this study is to review the scientific background of WCO recycling in the literature, which can be connected with the regulatory measures of WCO recycling in Taiwan since 2015. Furthermore, the updated information about governmental policies for promoting WCO as a mandatory recyclable resource (e.g., energy source) and its on-line reporting amounts in Taiwan is also analyzed to provide a demonstration case. Finally, an overview of available utilization of WCO as biodiesel, fuel oil, and non-fuel uses is briefly addressed in the paper.

## 2. Literature Review of the Scientific Background for WCO Recycling

Like most organic molecules, cooking oils are made of carbon, hydrogen, and oxygen, which further combine to form triglyceride. A triglyceride molecule is an ester chemically made from three fatty acids and one glycerol [1]. Depending on the chemical structures of fatty acids, cooking oils can be either saturated or unsaturated. Saturated fatty acids, mostly derived from animal fats, are more stable than unsaturated ones, meaning that the former do not easily become rancid and thus have longer shelf life. Due to the chronic health problem from intake of saturated fats (i.e., blood cholesterol levels increased), modern cooking oils are mostly derived from plant seeds (e.g., sunflower seed, soybean, olive, and rape seed) because they have double bonds between some of the carbon molecules. Therefore, fresh cooking oils are liquid at room temperature.

WCO or used cooking oils are bio-based oils that have been used for the purposes of cooking, frying, and other processing types in households, restaurants, fast foods, and the food-manufacturing industry. During these processes, physical and chemical changes will occur in cooking oil due to chemical reactions, including hydrolysis, thermal degradation, oxidation, and polymerization [7]. As a consequence, WCO contains many free fatty acids, thus generating bad odor and causing corrosion of metal and concrete elements. More importantly, this discarding has been classified as one of municipal wastes (household waste and similar commercial, industrial, and institutional wastes) because it can cause serious environmental problems. On the other hand, WCO is an underutilized bioresource in urban environments, posing potential valorization in the energy and material fields.

WCO represents an economic loss in edible oils. Therefore, it has been gaining more attention as a low-cost feedstock for producing biodiesel or other biofuels when compared to the use of edible oils as a food resource for human beings [8–20]. However, improving the recovery (collection/recycling) rate plays a critical role in the development of a WCO-to-biofuel production system [21]. Although the economic subsidies for the WCO-based biofuel producers may promote its conversion rate significantly, the performances of supply chain models in the WCO recycling are very different. As studied by Zhang et al. [21], it was found that the following factors will affect the recovery rates of WCO in China and Japan: subsidy beneficiary & intensity, lack of stick supervision, disposal cost of WCO, and biodiesel market size. For example, the restaurants may sell WCO to illegal collectors/recyclers because WCO recycling is a free market economy without legal supervision by the adequate waste management system.

## 3. Recycling of Waste Cooking Oil in Taiwan

### 3.1. Waste Recycling Policies in Taiwan

In Taiwan, the waste recycling policy was initiated by the authorization of the Waste Management Act (or called as the Waste Disposal Act), which was promulgated in 1974 [22]. According to the Act recently amended in Jun. 2017, the waste was defined as any removable solid or liquid substance or object,

- which is discarded;
- whose original purpose is lost, abandoned, not available, or unclear;
- which is not deliberately produced during the constructing, manufacturing, processing, repairing, selling, or using processes;
- which is generated from manufacturing processes, and is without feasible utilization technology or market economy value;
- which is announced as "waste" by the central competent authority (i.e., EPA).

Further, the waste is divided into general waste and industrial waste. Basically, general waste is approximately identical to MSW, which includes residential (household & dwelling) wastes, non-designated commercial & institutional (e.g., snack bar, small restaurant, clinic, school, retail, wholesale, small service activities) wastes, and municipal service wastes (e.g., street tree trimmings, gutter sludge) [23,24]. On the other hand, industrial waste refers to the waste that is produced from industrial, agricultural, commercial, institutional, and municipal service activities designated by the EPA, but does not include the waste generated by the employees themselves.

In Taiwan, general waste is further categorized into bulk waste, recyclable waste, food (kitchen) waste, hazardous waste, and general garbage (i.e., general waste other than bulk waste, recyclable waste, kitchen waste, and hazardous waste) under the provisions by the Waste Management Act (WMA). Herein, recyclable waste refers to the designated articles, packages, and containers officially announced by the EPA, which could cause concerns about serious environmental pollution and also possess one of the following characteristics:

- Be difficult to clear or disposal of.
- Containing components that do not readily decompose over a long-term period.
- Containing components that are hazardous substances.
- Be valuable for recycling and reuse.

Currently, the EPA has announced regulated (mandatory) recyclables, including iron, aluminum, glass, paper, plastic (PET/PVC/PE/PP/PS; plastic bag is not included), dry cell, motor vehicles, tire, lead-acid battery, home electrical appliances, information technology (IT, including computer and its peripheral devices) products, dry batteries, compact disc (CD), lightings, mobile phone and its charger (including charger and travel charger), and edible oil.

In order to recycle regulated recyclable wastes efficiently, the EPA has established the 4-in-1 Recycling Program since 1997 based on the principle of extended producer responsibility (EPR) [25–27]. This Program integrates the following four sectors:

- Community Residents

Residents are required to separate general waste from regulated recyclables, which may be sent to municipal collection teams (organized by local governments), private collectors licensed by the EPA, or to the second-hand market.

- Collectors and Recyclers

These private enterprises buy regulated recyclables from residents, municipal collection teams, community organizations, retailers, businesses, and others in order to recover available resources from these collected wastes and create gains in the recycling process.

- Local Governments

Municipalities and local governments (i.e., counties) organize collection teams to collect collected recyclables and other types of waste from community collection sites. These teams sell regulated recyclables to the collectors and recyclers and reserve part of revenue to fund local collection sites.

- Recycling Fund

The fund may be the most important sector because it subsidizes private collectors & recyclers and municipal collection teams. The sources of funds in the Recycling Fund come from the responsible enterprises (i.e., manufacturers and importers of regulated recyclables). These enterprises are required to pay fees to the Fund depending on the criteria set by the Recycling Rate Review Committee under authorization of the WMA. In addition, the Fund is managed by the Recycling Fund Management Board.

In the 4-in-1 Recycling Program, mandatory waste sorting began in 2005. Under the regulatory and promotional measures, the statistics on the collection amounts of mandatory recyclables are evident. Based on the ratio of generation amount for bulk waste/recyclable waste/food waste to the generation amount for total MSW, the recycling/reuse rate significantly increased from in 29.42% in 2005 to 60.23% in 2017 [28].

### *3.2. Waste Cooking Oil (WCO) Recycling Policies in Taiwan*

As mentioned above, the generation sources of WCO in urban environments can be grouped into the residential and commercial sectors. The former includes households and other types of dwelling units. The latter refers to the food manufacturer, chain fast-food, restaurant, snack bar, vendor, night market, and other forms of commercial activities producing WCO. According to the definition of waste in Taiwan, the WCO produced from the residential sector is a general waste. By contrast, the WCO produced from the commercial sector is an industrial waste, but is practically discarded as a general waste. In order to manage WCO from the commercial sector efficiently, the EPA decided to add WCO to the list of "general waste items that should be collected by municipal collection teams," under the authorization of the WMA, coming into effect on 24 October 2014. The WCO produced by households and institutions (e.g., schools, government agencies, etc.) can be collected by local environmental protection bureaus or sanitation teams, which are legally obliged to manage it. In addition, the WCO produced by small-scale commercial stores (e.g., restaurant, snack bar, vendor, night market) can be also collected by municipal collection teams. Meanwhile, to maintain effective WCO collection and to track its flow, the EPA announced that applications for permits were henceforth to be reviewed and issued by local governments. As of 1 January 2015, all WCO collectors and their vehicles are required to carry the permits whenever they are collecting WCO. Figure 1 shows the flows of WCO collection systems and recycling options in Taiwan. Furthermore, the EPA announced on December 10, 2014 that the following sources from commercial enterprises with producing WCO were required to submit their industrial waste management plans by on-line reporting system:

- Chain fast-food or restaurants (including branches and franchises) with a total capital of over NT$25 million.
- Food manufacturers with a total capital of over NT$2.5 million.
- Hotels (including branches) having more than 100 guest rooms.

According to the on-line reports from municipal collection teams during the period of 2014–2017 [28], the collected amounts of WCO significantly increased from 1599 tonnes in 2015, 3978 tonnes in 2016, to 12,591 tonnes in 2017 (Figure 2), reflecting on the above-mentioned WCO recycling promotion regulation effective in Oct. 2014. Actually, the collection amounts of WCO in

Taiwan annually exceed 25,000 tonnes based on the overall collection system (including municipal collection teams and private licensed collectors). The collected WCO is further processed by the following options:

- Domestic Reuse

Over 60% of collected WCO were proceeded and reused by domestic liscensed recyclers as energy sources (e.g., biodiesel, fuel oil) and chemical sources (e.g., soap, stearic acid). Table 1 lists the licensed CWO recyclers and their reuse methods in Taiwan. It should be noted that parts of the WCO-based biodiesel must be exported overseas because the government stopped biodiesel promotion in trucks in June 2014 due to vehicle safety (fuel tank and pipe clogging by biofuel-producing microbe). The reasons for stopping use of biodiesel in trucks will be described in detail in the subsequent section.

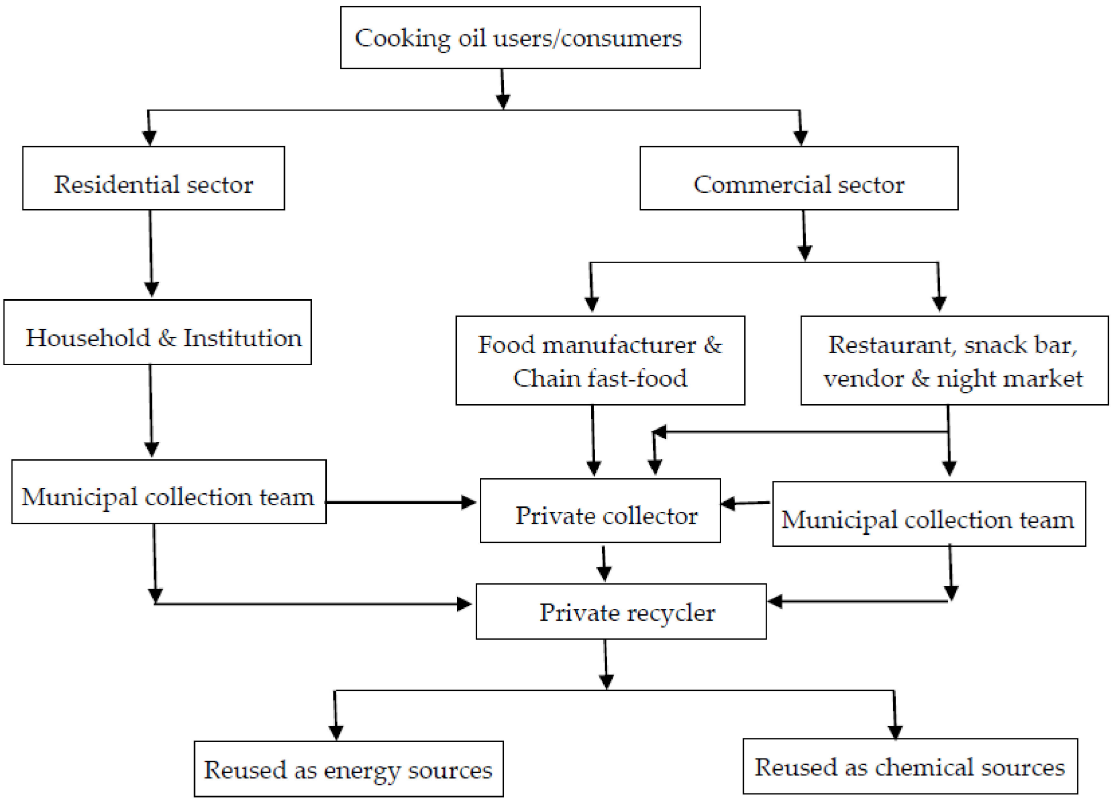


**Figure 1.** Flows of WCO collection systems and recycling options in Taiwan.

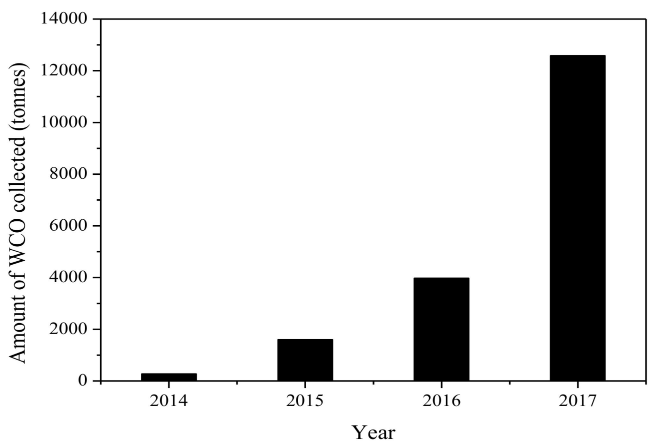


**Figure 2.** Amounts of WCO collection in Taiwan [28].

**Table 1.** Licensed CWO recyclers and their reuse methods in Taiwan.

| Location | Company No. | Reuse Method | Reuse Treatment Capacity (Tonne/Month) |
|---|---|---|---|
| Northern Taiwan | A | Feedstock for biodiesel<br>Feedstock for stearic acid<br>Feedstock for fatty acid methyl ester (blending with fuel oil) | 4800 |
| | B | Feedstock for stearic acid | 600 |
| Central Taiwan | C | Feedstock for biodiesel | 162.4 |
| | D | Feedstock for biodiesel<br>Feedstock for fatty acid methyl ester (blending with fuel oil) | 3000 |
| Southern Taiwan | E | Feedstock for biodiesel<br>Feedstock for fatty acid methyl ester (blending with fuel oil) | 1803.1 |
| | F | Feedstock for biodiesel<br>Feedstock for fatty acid methyl ester (blending with fuel oil) | 2600 |
| | G | Feedstock for soap | 520 |
| | H | Feedstock for soap | 80 |

- Overseas Reuse

About one-third of collected WCO were directly transported overseas for the purpose of biodiesel production or other available reuses. As mentioned above, the government stopped the promotion of boidiesel in trucks and buses, indicating that the domestic biodiesel market is not enough to match licensed biodiesel production capacity. On the other hand, countries such as in the European Union (EU) and Asia (e.g., Malaysia, and South Korea) are promoting biodiesel use at a somwhat lower tariff [29]. Although the EU still provided the trade protection (e.g., subsidy) to domestic biofuel feedstock producers, it is necessary to import biofuel from other countries (e.g., Taiwan) to meet market demand.

## 4. Available Utilization of Waste Cooking Oil (WCO)

### *4.1. Biodiesel*

As described above, reusing WCO as raw material for biodiesel production can reduce environmental pollution (compared to directly disposed of to the environment without treatment by wastewater treatment or incineration systems) and also improve urban air quality due to its renewable character and very low sulfur content. Biodiesel can be defined as the alkyl monoesters of fatty acids commonly derived from vegetable oils. Due to its renewable, non-toxic and biodegradable features, it can be used as an environment-friendly alternative for petroleum-based diesel fuel. Also, biodiesel has a more favorable emission profile when burning in the internal engine, which is indicative of low emissions of sulfur oxides ($SO_x$), carbon monoxide (CO), particulate matter, and unburned hydrocarbons. On the other hand, biodiesel has a relatively high flash point, thus making it less volatile and safer to transport, store, or handle than petroleum diesel. However, biodiesel also has some drawbacks, including more emission of nitrogen oxides ($NO_x$), less power output (due to higher oxygen content), and greater thickness (thus causing clogs in the fuel filters) when compared to regular diesel fuel [30]. However, the content of high free fatty acids (FFA) in WOC may become the main drawback for this potential feedstock in biodiesel production [20].

In biodiesel production, the commonly used way is to adopt the homogeneous, heterogeneous, and enzymatic catalysis for transesterification, which refer to a chemical reaction involving reactants (i.e., vegetable oil and alcohol) and catalysts to yield fatty acid alkyl esters (i.e., biodiesel) and glycerol. The by-product glycerol can be converted to hydrogen fuel via steam reforming [31]. In fact, the vegetable oil has been extracted, degummed, and neutralized before entering biodiesel production. The catalyst often uses a strong base, such as sodium hydroxide (NaOH), potassium hydroxide (KOH), or sodium methylate ($CH_3ONa$). In the transesterification unit, FFA contained in vegetable oil or WCO will react with alkali catalysts to produce soaps in parallel. Also, water in the reacting medium will greatly increase soap production due to the release of FFA as a result from the hydrolysis of triglyceride ester bonds. Because of its low cost and physicochemical properties, methanol is commonly used in the commercial process. After the reaction is completed, there exist glycerol and biodiesel products (i.e., methyl esters) formed in separate phases. The two products can be further separated by gravitational settling (decanting) vessel or centrifugal separator because the glycerol phase is much denser than biodiesel phase. These two solutions have significant amounts of the excess alcohol necessary to be recovered by flash vaporization. Before the separation of alcohol from the medium, the reacted mixture is sometimes neutralized at this step to remove soap residues caused by alkali catalyst. The resulting soap may act as an emulsifier and also to inhibit by-product glycerin separation. Therefore, it is usually necessary to pretreat the oil feedstock for lowering its FFA amount before it can be converted to specified biodiesel. Although the reactant methanol and by-product glycerin have been separated or removed, crude biodiesel still contains some impurities, such as soap and residual substances. These contaminants are usually removed by liquid-liquid extraction to meet the national specifications of the biodiesel fuel such as ASTM D6751 and EN 14214. In the water washing unit, the deionized water is mixed with crude biodiesel and gently agitated in a counter-flow column. In addition, the solution should be heated to about 60 °C to enhance the removal of residual substances like free glycerin. In order to reduce total water consumption and its subsequent wastewater treatment problem, the commonly used method is to lower the pH of crude biodiesel (<4.5) by adding acid. The soap dissolved in the biodiesel can be easily removed.

In order to require all diesel vehicles to be fueled with biodiesel and its blends compulsorily, the development of biodiesel standards started in the 1990s. There are two major specifications for establishing the quality requirements for biodiesel fuels: the ASTM D6751 (1999) in the USA and the EN 14214 (2003) in Europe. They have become the starting point for their own standards or specifications of biodiesel fuel developed by other countries. In Taiwan, the centrally responsible agency (i.e., MOEA) announced the national biodiesel specifications (CNS-15072) in 2007. As listed in Table 2 [32], the CNS-15072 in Taiwan basically follows the EN14214 in Europe. However, it should be noted that the standards of flash point and cold filter plugging point (CFPP) in Taiwan and Europe slightly differ. Among these properties, there has been considerable concern over the oxidative stability of biodiesel. This property will affect biodiesel greatly during extended storage, depending on the presence of air, water, heat, traces of metals, antioxidants, peroxides, and the nature of the storage container (or tank). For instance, the biodiesel fuel can be deteriorated through the hydrolysis and microbial population growth due to the presence of water. Another oxidation reaction can occur by auto-oxidation or oxidative polymerization, leading to the formation of resulting products with higher molecular weights. For this reason, the government in Taiwan thus stopped biodiesel blends (B2) promotion temporarily in 2014 because the humid air, warm weather, and low sulfur level in diesel fuels have led to fuel tank and filter clogging/plugging by microbial films and higher molecular weight contaminants (e.g., polymers, sediments and gums) formed during the storage of biodiesel or its blends. More significantly, these impurities will result in vehicle safety (e.g., ignition delay) and exhaust emissions at higher levels.

**Table 2.** Biodiesel (fatty acid methyl ester) standards CNS-15072 (Taiwan) and EN 14214 (Europe) [1].

| Property | Units | CNS-15072 (Taiwan) | | EN 14214 (Europe) | |
|---|---|---|---|---|---|
| | | Lower Limit | Upper Limit | Lower Limit | Upper Limit |
| Ester content | %(m/m) | 96.5 | - | 96.5 | - |
| Density at 15 °C | kg/m$^3$ | 860 | 900 | 860 | 900 |
| Viscosity at 40 °C | mm$^2$/s | 3.5 | 5.0 | 3.5 | 5.0 |
| Flash point | °C | 120 | - | 101 | - |
| Sulfur content | mg/kg | - | 10 | - | 10 |
| Carbon residue (at 10% distillation residue) | %(m/m) | - | 0.3 | - | 0.3 |
| Cetane Number | - | 51.0 | - | 51.0 | - |
| Sulfated ash content | %(m/m) | - | 0.02 | - | 0.02 |
| Water content | mg/kg | - | 500 | - | 500 |
| Total contamination | mg/kg | - | 24 | - | 24 |
| Copper band corrosion (3 h/50 °C) | rating | Class 1 | | Class 1 | |
| Oxidation stability, 110 °C | hours | 6 | - | 6 | - |
| Acid value | mg KOH/g | - | 0.5 | - | 0.5 |
| Iodine value | - | - | 120 | - | 120 |
| Linolenic acid methyl ester | %(m/m) | - | 12 | - | 12 |
| Polyunsaturated (≥4 Double bonds) methyl ester | %(m/m) | - | 1 | - | 1 |
| Methanol content | %(m/m) | - | 0.2 | - | 0.2 |
| Monoglyceride content | %(m/m) | - | 0.8 | - | 0.8 |
| Diglyceride content | %(m/m) | - | 0.2 | - | 0.2 |
| Triglyceride content | %(m/m) | - | 0.2 | - | 0.2 |
| Free glycerine | %(m/m) | - | 0.02 | - | 0.02 |
| Total glycerine | %(m/m) | - | 0.25 | - | 0.25 |
| Alkali Metals (Na + K) | mg/kg | - | 5 | - | 5 |
| Alkali Metals (Ca + Mg) | mg/kg | - | 5 | - | 5 |
| Phosphorus content | mg/kg | - | 10 | - | 10 |
| Cold filter plugging point (CFPP) | °C | - | 0 (B class) | - | +5~−26 [2] |

[1] Sources [30]. [2] Depending on seasons (summer/winter) and countries.

### 4.2. Fuel Oils

Another approach is to reuse WCO as an energy source in boilers or heaters due to its high heating value such as those of fuel oils (about 9000 kcal/kg) [33]. For instance, we can put the WCO into a combustion device, which burns it and sends the waste heat back into the WCO producer (e.g., restaurant) to produce hot water for use in the dishwashers and other kitchen facilities. In the literature [34], the feasibility study of using WCO as an auxiliary fuel by blending with different portions of diesel fuel in the furnace of laboratory waste incinerators demonstrated that this approach can reduce the emissions of persistent organic pollutants (POPs) such as polychlorobenzodioxins (PCDDs), polychlorodibenzofurans (PCDFs), and polychlorinated biphenyl (PCB). Therefore, WCO can be directly reused as an auxiliary fuel in the municipal solid waste (MSW) incinerators or cement-manufacturing rotary kilns without concerns about the emissions of hazardous air pollutants. Furthermore, the released heat from the combustion of MSW will make superheated steam for generating electricity via the combined heat and power (CHP) or cogeneration system. In addition, benefits of the CHP system in the waste-to-energy (WTE) plants can reduce air pollutants emissions, thus reducing GHG and air toxins (i.e., $SO_x$, $NO_x$ and Hg) emissions as compared to the burning of fossil fuels (e.g., coal, fuel oil) in the power plants.

### 4.3. Non-Fuel Related Uses

It is well known that triglycerides are the predominant component of edible oils. The minor constituents include mono-glycerides, diglycerides, free fatty acids, phosphatides, sterols, fatty alcohols, fat-soluble vitamins, and other components. Therefore, oils and fats can be essential components of an animal diet, as they provide high energy diets, as well as some essential constituents not synthesized by animals. In this regard, WCO seemed to be reused as animal feed additives [35]. However, the compositions of WCO may be different from those of vegetable oils due to thermal and other reactions (e.g., hydrolysis, oxidation, and polymerization) at high temperatures during the frying [2]. Although WCO was pretreated by filtration medium initially, the presence of some harmful components (e.g., dioxins and polycyclic aromatic hydrocarbons) led to the promulgation of some strict laws against the utilization of WCO in animal feed. In 2014, for instance, the central competent authority (i.e., Council of Agriculture, COA) in Taiwan promulgated the regulation governing the restriction of WCO reused in animal feed and the strict measures of imported food oils used in animal feed.

One of the easiest approaches to utilizing WCO is to make soap because it is made of a hydroxide base (Na or K) of naturally occurring fatty acids derived from vegetable oils or animal fats [36]. The WCO-based soap can be further used in a variety of degreasing and washing purposes. This soap-making process is based on saponification reaction under the addition of alkali hydroxide (i.e., sodium or potassium hydroxide). In order to eliminate harmful and unpleasant odorous substances, WCO must be pretreated by filtration method before using it in the soap production.

As mentioned above, vegetable oils are too viscous and reactive to atmospheric oxygen. These drawbacks must be modified to be availably used in fuels and other biobased products like lubricants. The beneficial aspects of WCO-based lubricants possess easy biodegradability and low toxicity compared to mineral-based lubricants [37]. In addition, these biobased lubricants have low volatility because of the higher molecular weights of triglyceride structure and narrow viscosity change with temperature.

Basically, WCO comprises ester bonds of long chain fatty acids (i.e., triglyceride molecules). Therefore, the incorporation of hydrolyzed enzyme to WCO can produce C-18 fatty acids such as stearic acid and oleic acid, depending on its oil precursor [38]. Lipases are unique biocatalysts in the production of fatty acids because of positional specificity and selectivity in acylglycerol. These fatty acids derived from WCO can be further used in the production of soaps, detergents, cosmetics, and other care products.

## 5. Conclusions and Prospects

WCO, which is mostly generated from residential and commercial sectors in huge quantities, represents an underutilized resource in modern society. In fact, it is a renewable resource, which can be reused to produce fuel oils and biobased products in the replacement of petroleum-based mineral oils. However, the major obstacle for reusing it as energy and chemical sources is the high cost in collection, transportation, and pretreatment (e.g., purification). In order to promote WCO recycling and to ensure food security by preventing it from re-entering the food chain, it was officially listed as one of the mandatory recyclable resources in the MSW by the EPA in Taiwan under the 4-in-1 Recycling Program since 2015. It shows that the collected amounts of WCO from residential and commercial sectors in Taiwan significantly increased from 1599 tonnes in 2015 to 12,591 tonnes based on the on-line reporting database. Among the collected WCO, about two thirds were currently proceeded and reused by domestic liscensed recyclers as energy sources (e.g., biodiesel, fuel oil) and chemical sources (e.g., soap, stearic acid). The rest of the collected WCO were directly transported overseas for the purpose of biodiesel production or other available reuses. It should be noted that the government in Taiwan temporarily stopped biodiesel blends (B2) promotion in the trucks/buses since May 2014 due to the fuel tank and filter clogging/plugging. Although biodiesel production is one of the best available utilization options of WCO in Taiwan and other countries or regions, other energy uses in the industrial boiler and MSW incinerators are also practical without concerns about air pollutants emitted. Regarding non-fuel related uses, WCO can also be utilized to produce some biobased products such as soap, stearic acid, and lubricant. In brief, the reuse of WCO as energy and material sources will amount to valuable urban mining for the purpose of pursuing the goals of zero MSW disposed of, and a circular economy.

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