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EGGSHELL AS HETEROGENOUS CATALYST FOR BIODIESEL PRODUCTION FROM WASTE COOKING OIL AND OPPORTUNITIES IN CHINA

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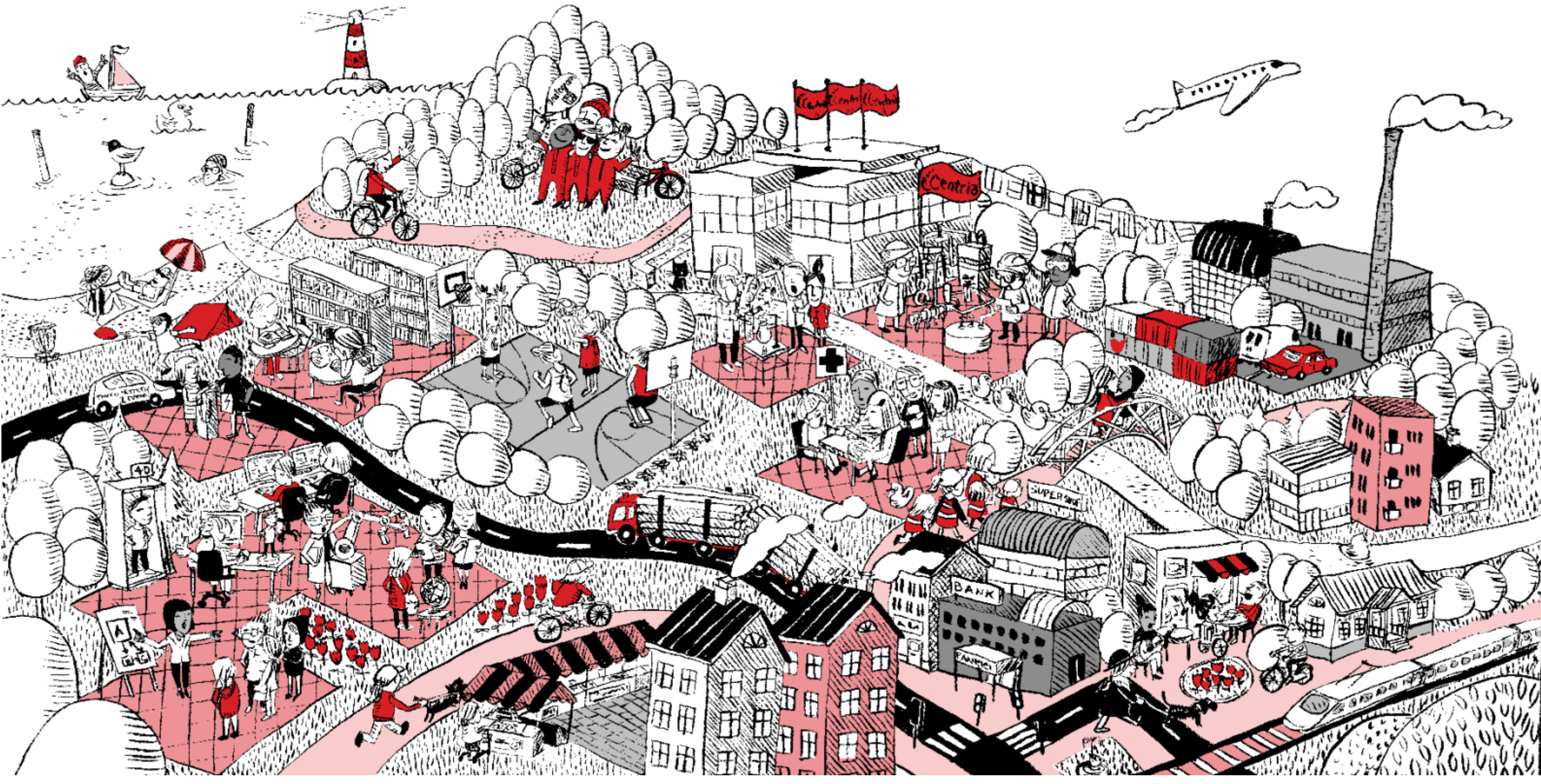

ABSTRACT

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Biodiesel production from waste cooking oil using biomass-based solid heterogeneous catalysts has gained attention. Calcium oxide catalyst can be derived from waste eggshells. This kind of catalyst has the advantages of low cost, recyclability, and environmental friendliness. This study examined the factors affecting the transesterification process affecting the yield and gave suggested values, namely the catalyst concentration was 1.5 wt.%, the molar ratio of methanol to oil was 12:1, the reaction time was 2 h, the reaction temperature was 65°C, and the stirring rate was 250 rpm. Then, this study also presented a potential improvement measure—ultrasonic assist system.

In addition, this thesis also shows the opportunities for the future development of this method in China. It also discusses the five aspects, biodiesel opportunities, production cost, waste cooking oil collection, eggshell catalyst and value added by-products. With the world's largest population, China has a huge demand for energy. Although it has experience in making biodiesel from waste cooking oil, there are still problems in waste oil collection, government management, and technical support. Efforts are still needed for large-scale commercialization.

Key words
Biodiesel production, Eggshell, Transesterification, Waste cooking oil

CONCEPT DEFINITIONS

List of abbreviation

ASTM D6751	Standards and specifications for biodiesel blended with middle distillate fuels
BET	Biodiesel enterprise take-back
B10	Biodiesel is mixed with diesel, and biodiesel accounts for 10%
B20	Biodiesel is mixed with diesel, and biodiesel accounts for 20%
CaO	Calcium oxide
CO	Carbon monoxide
CO_2	Carbon dioxide
$CaCO_3$	Calcium carbonate
$Ca_3(PO_4)_2$	Calcium phosphate
FFA	Free fatty acid
FAME	Fatty acid methyl ester
H_2SO_4	Sulfuric acid
$MgCO_3$	Magnesium carbonate
NaOH	Sodium hydroxide
Na_2SO_4	Sodium sulphate

PI	Process intensification
TPT	The third party take-back
TG	Triglyceride
WCO	Waste cooking oil

List of units

cm	Centimeter
mA	Milliampere
mt%	Mass fraction
rpm	Revolutions Per Minute

ABSTRACT
CONCEPT DEFINITIONS
CONTENTS

FIGURE

TABLE

1 INTRODUCTION

Energy is an important guarantee for a country's economy and security, and it plays an important role in industry, transportation and other sectors. With the rapid growth of the world's population and the development of technology, people's demand for energy is also increasing. The recovery rate of traditional fossil fuels is no longer enough to meet the consumption of people. Besides, the environmental pollution from fossil fuels has also received attention, such as the large amount of greenhouse gas emissions. The search for alternative energy sources has become an important task. As a renewable energy source, biodiesel has been gaining attention in recent years. It is considered to be one of the most alternative energy sources of fossil fuels. The main component of biodiesel is fatty acid methyl ester (FAME). It can be produced from plants, edible oils, non-edible oils and algae. (Hoekman, Broch, Robbins, Ceniceros & Natarajan 2012, 143-169.)

Waste cooking oil (WCO) is the oil left after cooking and it is considered as a potential option for large-scale commercial production. Nearly 16.5 million tons of WCO are produced globally every year. Due to some imperfect management some WCO is discharged directly into the sewer or river. The water-insoluble properties and the toxic substances contained in WCO can cause many problems. If WCO can be used as a raw material for biodiesel, it will be another phenomenon. On the one hand, it can alleviate the government's pressure on WCO management. On the other hand, the use of waste raw materials to produce new energy is also more suitable for sustainable development. (Khodadadi, Malpartida, Tsang, Lin & Len 2020.)

Biodiesel production is mainly carried out through the transesterification process, which requires the aid of a catalyst. Homogeneous catalysts have been criticized for their tendency to trigger saponification reactions and affect the quality of biodiesel. Enzyme catalysts are not yet commercially available due to high production costs. In recent years, heterogeneous catalysts have attracted people's interest because they can be easily recycled and reused. The production of catalysts using different substances has been reported. For example, eggshells, mollusk shells, chicken manure, biochar, scale. (Tan, Abdullah & Nolasco-Hipolito 2015, 589-603; Gaur, Mishra, Chowdhury, Baredar & Verma 2020.)

In this study, biodiesel will be produced from waste cooking oil with eggshells as heterogeneous catalyst via transesterification process. At the same time, the study will focus on the influencing factors during transesterification process, such as catalyst concentration, methanol molar ratio, reaction time, reaction temperature and stirring speed. Besides, the opportunity of this potential biodiesel production method in China’s future will be mentioned later from demand for biodiesel, cost analysis of whole process, challenges of feedstock collection and potential advantages.

2 RESEARCH STATUS AND THEORETICAL BASIS

With the increasing awareness of environmental protection, people gradually start to pay attention to the development of new energy. New energy ought to be not difficult to store and ecofriendly. Biodiesel is a good option. (Bhatia, Bhatia, Jeon, Pugazhendhi, Awasthi, Kumar, Kumar, Yoon & Yang 2021, 2-3.) Cooking oil has become a necessity in people's daily life. The generation of WCO is also inevitable. However, if WCO can be used in biodiesel development, it will change the current dilemma. This part will talk about the current situation of WCO and the development of biodiesel. After that, the theoretical basis of biodiesel preparation using WCO, and the catalyst issue will be presented.

2.1 Development of biodiesel

In recent years, biodiesel known as the most promising renewable fuel because of its biodegradability, sustainability and friendliness to the environment. Many countries around the world are producing biodiesel based on different feedstocks, such as Brazil, USA, Malaysia, Argentina, and Spain. Biodiesel is a mixture of esters (C14-C24) which are long chains. Glycerol is the main by-product of the production process, which can be used as a combustion improver for biodiesel/diesel and thus increase the economic benefits of the biodiesel industry. (Mofijur, Siddiki, Shuvho, Djavanroodi, Fattah, Ong, Chowdhury & Mahlia 2020.) Biodiesel does not contain sulfur, so it is very friendly to the environment, which can be a good way to mitigate the increasing global warming. In addition, it is easy to store, easy to transport, and has similar combustion characteristics to fossil fuels for use in existing engines. (Bhatia et al. 2021.)

According to the study of Mofijur et al. (2020), corn, vegetable oil, waste oil, animal fat, and algae can be raw materials in biodiesel production. Biodiesel can be roughly classified into three generations according to different raw materials. The first generation of biodiesel mainly comes from grain and edible oil. However, biodiesel based on edible crops will compete with human food consumption, which in turn will lead to an increase in global food prices. Therefore, starting from the second generation of biodiesel, the choice of feedstock became inedible sources. For example, animal fats, waste oils, inedible oils or non-edible plants. The third generation of biodiesel relies on algae plants, especially microalgae. TABLE 1 presents the advantages and challenges faced by each of the three generations of biodiesel.

TABLE 1. Advantages and challenges of three generations biodiesel (Adapted from Mofijur et al. 2020, 3-4.)

Biodiesel types	Advantages	Challenges
1st generation	Renewable source Environmentally friendly Easy conversion	Compete with food crops Rising cost of food Land scarcity
2nd generation	Renewable source Environmentally friendly Does not compete with food crops	Land and water use competition Requires sophisticated downstream processing technologies High production cost
3rd generation	Renewable source Environmentally friendly No conflict with food or land Higher growth rate	High initial production and setup costs for economic viability Insufficient biomass production for commercialization

The table above illustrates the advantages and challenges of each of the three generations of biodiesel. The traditional first-generation biodiesel process is simple and easy to manufacture. However, it affects the food that people depend on for survival. The second-generation biodiesel solves the problem of food competition, but the subsequent treatment process is complicated, which leads to the increase of cost. New technologies should also be developed to reduce costs if large-scale applications are required. The latest generation of biodiesel based on algae as raw material has solved the shortcomings of the first two generations perfectly, but there are problems of insufficient yield and high initial cost. (Mofijur et al. 2020, 3-4.) This thesis will focus on the second generation of biodiesel based on waste cooking oil as raw material.

2.2 Waste cooking oil in biodiesel production

WCO is the used cooking oil in the catering industry. It can produce biodiesel by transesterification reaction. In this section, the research is centered on two main parts. The first aspect is the current status of WCO and the reason why WCO is getting attention. On the other hand, the comparison of WCO-based biodiesel with conventional diesel and the blending of biodiesel with diesel will be presented.

2.2.1 Waste cooking oil as feedstock

Waste cooking oil is obtained through frying and cooking processes. As the global population continues to increase, the global food consumption levels have increased accordingly. This has led to a large increase in WCO. (Bhatia et al. 2021.) The annual production of WCO in the world is about 16.5 million tons. (Khodadadi et al. 2020, 1-2.)

There is a significant difference in the composition of edible oil and waste cooking oil. This is mainly due to the fact that during cooking, the cooking oil is exposed to high temperatures and many physical or chemical changes occur in the water in the food. In general, WCO is a mixture of fatty acids and triglycerides. However, during the frying process, some derivatives can contaminate it, such as free fatty acids (FFA) and heterocycles. Among them, triglyceride can be a raw material for biodiesel and production of soap. It is also considered as the most environmentally friendly way to process WCO. (Khodadadi et al. 2020.)

WCO has attracted people’s attention for two main reasons. On the one hand, WCO is two to three times cheaper than crude oil, which makes it a potential feedstock of new energy. On the other hand, WCO is produced in large quantities, and if it can be recycled, it will not only contribute to sustainable development, but also solve environmental problems and reduce the harm to people. Environmental issues have always been the main reason why WCO has been criticized. Due to poor regulation and imperfect system, many WCOs are disposed of into the sewer. However, because WCO is not easily soluble in water, it can pollute water quality or affect natural flora and fauna. In the United States, nearly half of the sewer clogging problem is caused by grease and WCO, and removal operations cost nearly

$25 billion annually. In China, about 40-60% of WCOs return to the table through various illegal routes because of insufficient regulation. Reused WCOs are very harmful to the human liver and heart. (Zhao, Wang, Zhang, Chang & Hao 2021.) In contrast, if WCO is used to produce biodiesel, both environmental pollution and hazards to human body will be significantly reduced. (Khodadadi et al. 2020.)

2.2.2 Properties of biodiesel obtained from waste cooking oil

ASTM D7651 is one of the standards that stands for American Society for Testing and Materials. It specifies the physical and chemical properties of biodiesel blends, such as flash point and kinematic viscosity. The TABLE 2 shows the comparison between the biodiesel produced based on waste cooking oil and ASTM D6751 standard in terms of different properties. It is not difficult to find that the flash point of biodiesel made from WCO is only 63℃. The low flash point often affects the flammability of the fuel, which is a drawback that cannot be ignored. But this problem can be mitigated if biodiesel is blended with diesel fuel. At present, there are two main blending methods with 10% (B10) and 20% (B20) of biodiesel respectively. (Pauline, Sivaramakrishnan, Pugazhendhi, Anbarasan & Achary 2021.)

TABLE 2. Comparison of characteristics between WCO biodiesel and ASTM D6751 (Adapted from Pauline et al. 2021.)

Properties	WCO biodiesel	ASTM D6751
Cloud point (°C)	13.4	-3~12
Flash point (°C)	63	Min 130
Fire point (°C)	72	Min 53
Kinematic viscosity (mm^2/s at 40 °C)	5.1	1.9~6.0
Density (kg/m^3)	877	860~900
Cetane number	48	Min 45

Pauline et al (2021) suppose B20 blended diesel is more advantageous in terms of fuel consumption and energy density. In addition, emissions are also a major concern. If biodiesel is not effective in reducing greenhouse gas emissions, it will be a failed solution. Both B10 and B20 have lower emissions of carbon monoxide and hydrocarbons than fossil fuels. This is due to the high oxygen content of biodiesel, which is a more complete combustion reaction and reduces carbon monoxide emissions. Meanwhile, the higher cetane number can shorten the ignition is delay, which maximizes combustion and reduces hydrocarbon emissions. In terms of CO_2 emissions, B20 is better, which emissions are consistently lower than conventional diesel. Overall, the B20 blend ratio is optimal. (Pauline et al. 2021.)

2.3 Transesterification method

The production process of biodiesel has been improved with the advancement of technology. Currently, biodiesel can be produced by two different types of methods, physical and chemical. The physical methods include blending and microemulsion. Chemical methods include pyrolysis and transesterification processes. (Mofijur et al. 2020, 4-5.) Each of these methods has its own advantages. Among them, the Transesterification process is the most widely used method in biodiesel production. It has two very distinct advantages over other methods, one is that the raw material that is not fully reacted can be recycled, and the other is that its by-product glycerol can also be profitably used as a commodity. In this process, three moles of a light alcohol (usually methanol) are reacted with one mole of triglyceride. This process usually requires the action of a catalyst, and the temperature is usually between 60-70 degrees Celsius. At the end of the reaction, the unreacted alcohol can be re-added to the reaction, saving on feedstock costs. This is one of the reasons why this method is widely used. In addition, the by-product of the process (glycerol) can be sold in the market, again reducing costs. (Tabatabaei, Aghbashlo, Dehhaghi, Panahi, Mollahosseini, Hosseini & Soufiyan 2019.)

As the FIGURE 1 shows below, FIGURE 1a. illustrates the total chemical equation of transesterification process. As described previously, one mole of triglycerides reacts with three moles of methanol in the presence of a catalyst and achieves methyl esters and glycerol. Among them, methyl esters are the components of biodiesel. A triglyceride is an ester obtained from glycerol and three long chain fatty acids. Triglycerides are the principal constituents of muscle versus fat in people and other vertebrates, in addition to vegetable fat. It is likewise present in vast numbers in the WCO. The reaction actually consists of three successive reversible reactions, as shown in FIGURE 1b. At the very beginning, methanol reacts with triglycerides (TG) to obtain diglycerides. Next, methanol reacts with diglycerides to obtain glycerol monoglyceride. Finally, methanol reacts with monoglyceride again to obtain glycerol. All three of these steps yield one mole of FAME, for a total of three. (Tan et al. 2015, 589-603.)

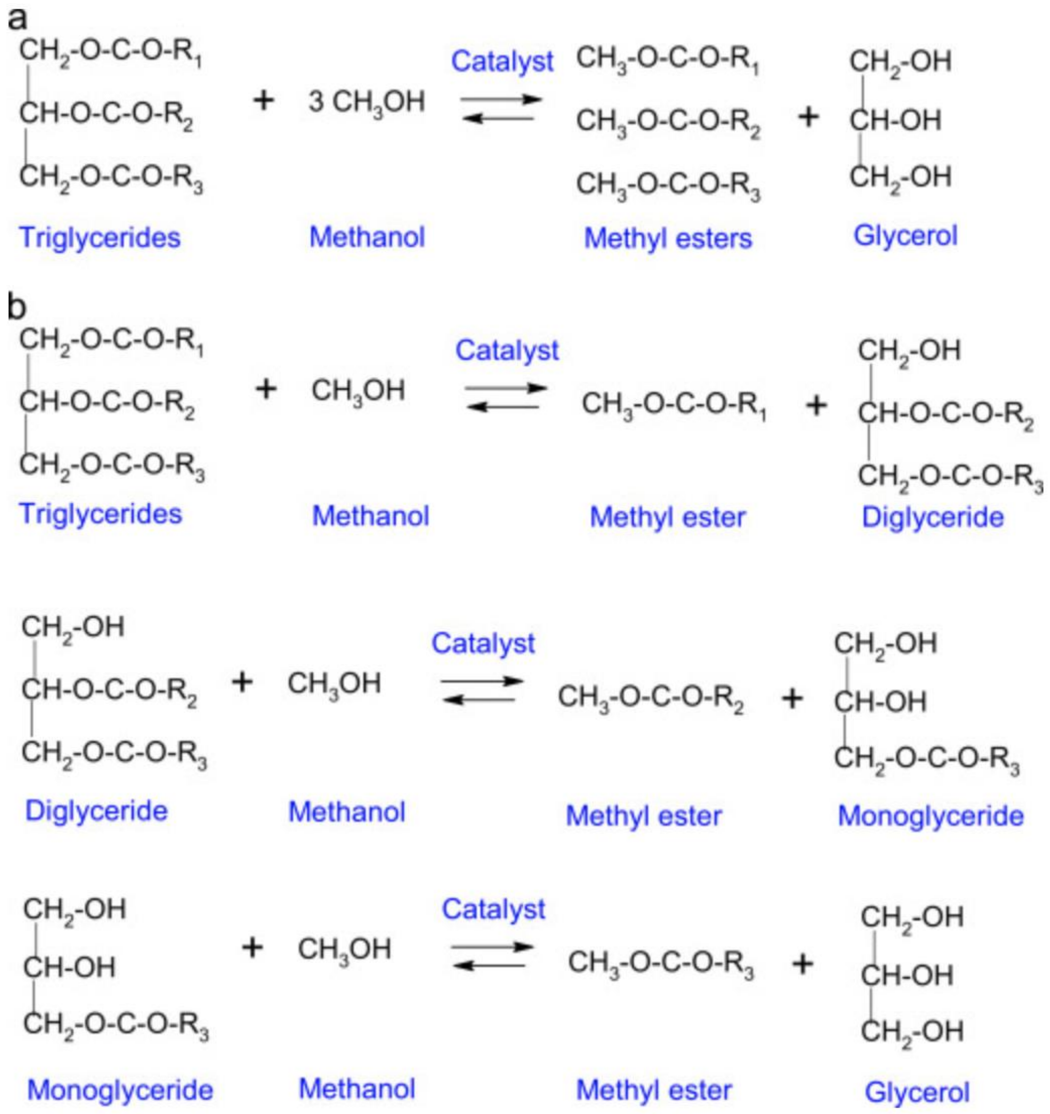

FIGURE 1. Chemical equation of transesterification process in biodiesel production (Adapted from Tan et al. 2015, 589-603.)

These reactions are usually considered to be second-order or pseudo-second-order reactions due to the fact that their reaction rate constants are different for the forward and reverse reactions. Of the three reactions, the first one proceeds more slowly. The reason for this is the mutual insolubility of the oil and methanol and the transfer limitation caused by the production of diglycerides. On the contrary, the second reaction occurs the fastest because the methyl ester produced by the reaction can act not only as a solvent but also as a co-solvent for the reaction, which can facilitate the reaction. However, the reaction rate does not continue to increase in the third step because there are fewer and fewer reactants left and the reaction rate tends to converge. (Tabatabaei et al. 2019.)

2.4 Catalyst in biodiesel production

Catalyst is a compound used to increase the reaction rate of the transesterification process. It increases the rate of transesterification mainly by the pathway of reducing the activation energy. Catalysts are involved in the reaction but do not undergo permanent changes during the reaction as they return to their original state again. Nowadays, catalysts are classified in two main ways. The first is according to chemical properties, which can be classified as acids, bases, and enzymes. The other is based on its own composition and can be classified as homogeneous, heterogeneous and enzymatic catalyst. A homogeneous catalyst is a reaction in which the catalyst and the reactants are in the same phase and no phase boundary exists. In contrast, heterogeneous catalysts are in different phases with one or more reactants. Typically, solid metals and metal oxides are used to catalyze reactions with gaseous or liquid reactants as heterogeneous reactions. Enzyme catalysts refer to enzymes, which are a class of proteins produced by living organisms with efficient and specific catalytic functions. Some scientists may also classify catalysts that incorporate nanotechnology into a separate category called nano catalysts. (Gaur et al. 2020; Ball& Key 2020.)

To date, a wide variety of catalysts have been used for biodiesel production. Researchers have found that although enzyme catalysts yield a higher purity product, the reaction time is too long and expensive for large-scale commercial production. Homogeneous catalysts, on the other hand, are highly efficient and have short reaction times, but produce large amounts of wastewater in the downstream process. These wastewaters are highly corrosive to the environment and therefore require the installation of special equipment. For these reasons, the search for an environmentally friendly and non-corrosive catalyst with low cost was initiated. As a solid heterogeneous catalyst, calcium oxide (CaO) has received much attention. Extraordinary it can be produced from renewable energy sources such as eggshells, scallop shells, snail shells, and chicken bones. (Gaur et al. 2020.)

In this thesis, CaO will be produced from eggshells. This is very helpful to reduce the cost of the whole production process. Besides, the use of waste as catalyst is also more in line with today's world strategy of sustainable development and better for the environment. (Gaur et al. 2020.) In addition to the advantage that it can be made from waste, CaO is also popular among the available alkaline earth metal oxides for its own physicochemical properties. For example, it has low cost, long lifetime and possesses high activity under mild conditions. (Chung, Tan, Chan, Kansedo, Mubarak, Ghasemi & Abdullah 2019.)

It can be foreseen that CaO catalysts derived from waste eggshells can be effectively used for the production of second generation biodiesel.

3 BIODIESEL FROM WASTE COOKING OIL WITH EGGSHELL

In this section, firstly, the composition and preparation process of eggshell catalyst will be discussed. Next, the process of biodiesel preparation from WCO will be shown, including pretreatment process, transesterification process, and product separation. Then the influencing factors of the whole process approach will be discussed, including the catalyst amount, the molar ratio of methanol to WCO, reaction time, reaction temperature and stirring rate. Finally, a potential improvement method, ultrasound assisted system, will also be introduced.

3.1 Catalyst preparation

Generally, the structure of eggshell can be divided into three layers. At the outermost part is the outer layer of the epidermis, also called the stratum corneum. In the second position, the middle layer, which can also be called the spongy layer, has many large pores and is mainly composed of $CaCO_3$. This is also the main site of conversion into a transesterification catalyst. In addition, the outer surface of the eggshell is covered with a special mucin, which acts as a soluble plug for the pores in the eggshell. (Tsai, Yang, Lai, Cheng, Lin & Yeh 2006, 488-493.) In total, the eggshell is usually composed of approximately $CaCO_3$ (96%), $Ca_3(PO_4)_2$ (1%), $MgCO_3$ (1%), organic matter (mainly proteins) and water. (Wang, Yan & Zhao 2020.)

It is important to note that eggshells produced in food processing plants inevitably consist of eggshells and eggshell membranes. The eggshell membrane is located between the egg white and the inner surface of the eggshell. There are two shell membranes located around the egg, a thick outer membrane attached to the shell and a thin inner membrane. The total thickness of these two membranes is about 100 μm. Both membranes are composed of protein fibers that are arranged to form a semi-permeable membrane. (Tsai et al. 2006, 488-493.) When calcined at temperatures between 700 and 1000°C, $CaCO_3$ can be converted to CaO. (Wang et al. 2020, 4.)

In the current study, the main sources of spent eggshell catalysts are chicken eggshells and ostrich eggshells. Both of them are prepared in the same way. First, the collected eggshells were washed with tap water and then rinsed with distilled water. The purpose is to remove impurities, such as food residues, attached to the eggshells. Next, the eggshell membrane consisting of protein fibers should be removed, which is not a required component of the catalyst. They are usually translucent white. The shells are then placed in an oven and dried at 100°C overnight. This removes excess moisture and improves the quality of the catalyst. After drying, the eggshells are crushed into small pieces and ground with a grinder. The fine powder obtained by grinding is passed through a 0.5 mm sieve. Finally, the fine powder is heated in a muffle furnace at 1000°C for 4 hours and then removed. The removed fine powder is transferred to a sealed vacuum flask for storage immediately after cooling to prevent contamination by water or carbon dioxide in the air. (Tan, Abdullah, Nolasco-Hipolito & Taufiq-Yap Y 2015, 58-70; Kamaronzaman, Kahar, Hassan, Hanafi & Sapawe 2020, 324-328.)

3.2 Production process of biodiesel from waste cooking oil

WCO is usually collected from restaurants or kitchens. WCO is cooking oil that has been fried and will contain some food residue and water after collection. Before the preparation process starts, the WCO must be treated first to make it as pure as possible so as not to affect the quality of the biodiesel. This is the main target of the pre-treatment process (Abukhadra, Basyouny, EI-Sherbeeny, EI-Meligy & Elgawad 2020, 17, 2-3.). Gupta & Rathod (2018, 169-178) gave a specific WCO pretreatment process that can effectively remove excess solid impurities and water. The specific operation process is as follows; muslin cloth is commonly used to perform the filtration process of WCO. After that, heat it at 120 degrees Celsius for 30 minutes to remove the excess water.

The study by Kamaronzaman et al. (2020, 324-328) mentioned that after the filtration treatment of WCO, the free fatty acid (FFA) content of WCO should be determined. This is related to whether the subsequent transesterification reaction can proceed smoothly. The method of FFA values was determined as follow according to Susilowati, Hasan & Syarif (2019). 5 grams of WCO was mixed with 50 milliliters of methanol at 98% concentration and 2-3 drops of phenolphthalein indicator. Then titrated using sodium hydroxide solution. The value of FFA was obtained based on equation (a).

$$FFA(\%) = \frac{\frac{256g}{mol} \times V \times N}{m \times 1000} \times 100\% \qquad \text{(a)}$$

where: V is volume of NaOH,

N is concentration of NaOH,

m is sample mass.

Tan et al (2015, 58-70) also mentioned how the FFA value affects the transesterification process. If the value of FFA is below 3 wt.%, the transesterification process is carried out directly. However, if the FFA value is higher than 3 wt.%, no reaction occurs. At this point, a two-step esterification process is required. That is, a new pretreatment process, acid esterification, is added before the transesterification process. This work is necessary to reduce the FFA content and allow the transesterification process to proceed properly. The specific operation of the acid esterification part will be illustrated below.

Kamaronzaman et al (2020, 324-328) described in the case of FFA values above 3 wt.% the acid esterification operations that need to be performed. First, WCO was heated at 110°C for 24 h. Then, 25 ml of methanol with 0.05 ml of concentrated sulfuric acid was added and mixed in a 250 ml conical flask and stirred. Subsequently, 50 ml of WCO at 65°C was added to the conical flask and preheated. The mixture was allowed to stir again at 65°C for one hour. Finally, the resulting WCO was preheated to about 65°C. The WCO treated using this method can later be reacted directly with methanol and catalyst.

After pre-treatment process, the transesterification process will be carried out. In the study by Tan et al (2015, 58-70) the process was carried out in an orbital shaker, which facilitated better contact of the reactants. First, the prepared Cao catalyst (eggshell catalyst) was mixed with methanol at 65 °C and shaken continuously for one hour to form the methoxide mixture. Next, the freshly obtained methoxide mixture was added to the preheated WCO and stirred vigorously (WCO should also be preheated to 65 °C).

Bhatia et al. (2021) discussed the purification of biodiesel and the recovery of by-products. The biodiesel obtained after the transesterification process is not pure and also contains catalyst, excess methanol and glycerol as a by-product. Further separation and purification are necessary to reduce subsequent adverse effects, such as damage to the engine and impact on efficiency. The catalyst used in the production process varies, usually influences the method used in the separation and purification. Centrifugation is used to separate the different substances to obtain clean biodiesel. This method is particularly suitable for reactions that use a solid biomass heterogenous catalyst. The centrifuge can easily separate the catalyst, glycerol, methanol and biodiesel. The biodiesel will be at the top and the glycerol and catalyst will be at the bottom. Hot distilled water will be used for washing and purification of the collected biodiesel. In the end, biodiesel needs to be dried to remove the water. The collected methanol and catalyst can be re-involved in the reaction again to reduce the cost. The by-product glycerol also contains many impurities, such as unsaturated fatty acids, inorganic salts, methanol, and glycerol esters, which affects its utilization. A combination of acidification, phase separation, neutralization and extraction recovery method can yield glycerol with a purity of up to 93.3%, which can allow it to be used to produce a more valuable product and increase the total profit of biodiesel production.

By looking at the FIGURE 2 below, the whole process can be understood more visually. In industrial production, the FFA value of the collected WCO may vary due to different sources and impurities. Therefore, the determination of the FFA value of the collected WCO is the most important part at the beginning of the process. The eggshell catalyst and methanol should be mixed well before they are added into the transesterification process. At the end of the separation process, obtain biodiesel. At the same time, the remaining catalyst and methanol can involve in the next production process. After that, the washing and drying process can better improve the quality of biodiesel. (Tan et al. 2015, 58-70.)

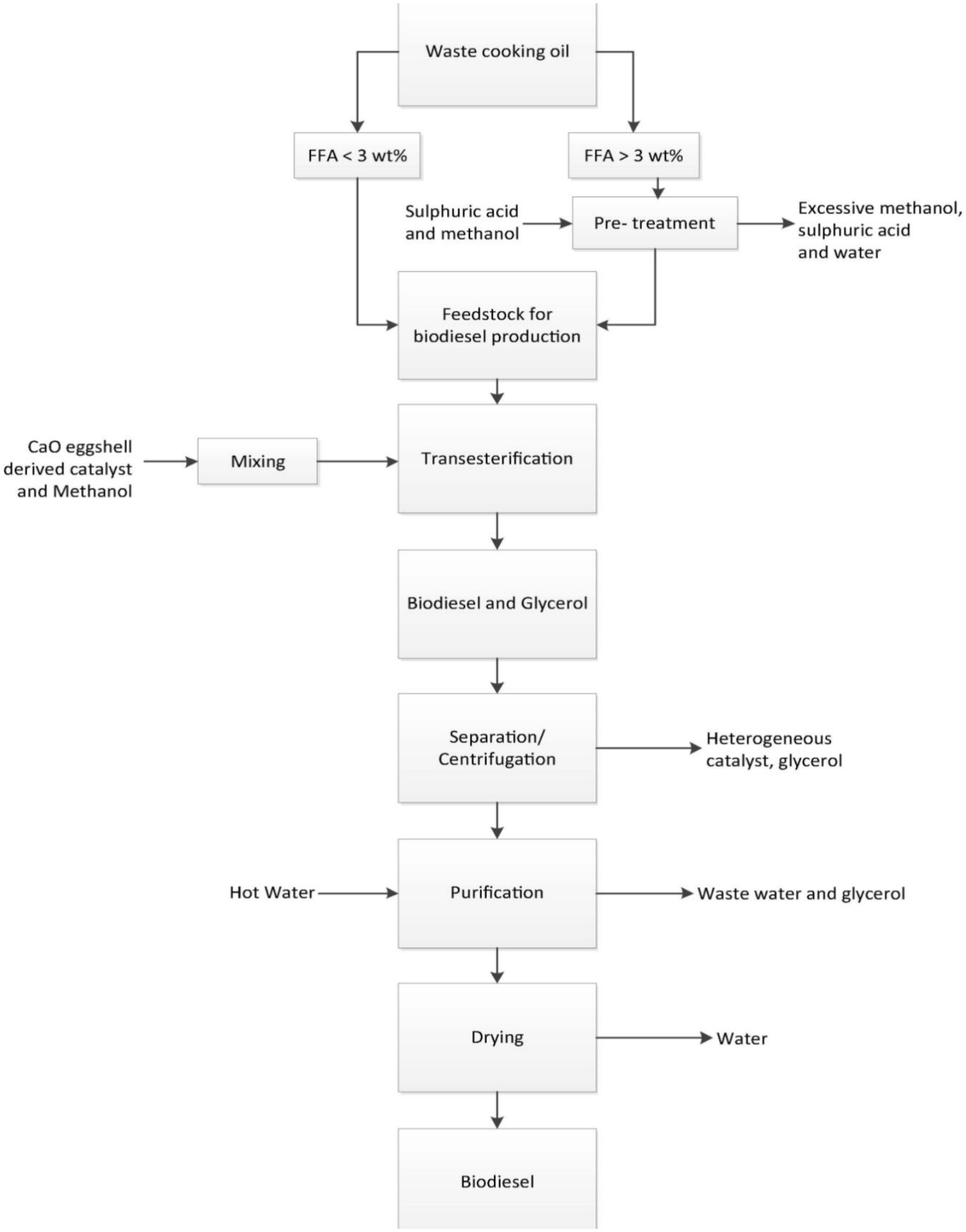

FIGURE 2. Process of biodiesel from waste cooking oil (Adapted from Tan. et al 2015, 58-70.)

3.3 Influence factors of biodiesel yield

There are five main factors that affect the transesterification process, which are catalyst concentration, molar ratio of methanol to oil, reaction time, reaction temperature and stirring speed. They affect not only the final biodiesel yield, but also the cost of production, such as the use of electricity. The yield of biodiesel is an important factor to measure the reliability of the transesterification process. Calculation equation is shown as equation (b) (Abukhadra et al. 2020, 17, 2-3.). In this paper, these five factors will be analyzed in turn and the optimal values will be given.

$$Biodiesel\ yield(\%) = \frac{(Weight\ of\ biodiesel \times \%FAME)}{Weight\ of\ oil} \times 100\% \qquad \text{(b)}$$

3.3.1 Effect of eggshell catalyst concentration

The study of Tan et al. (2015, 58-70) choose ostrich eggshells and chicken eggshells as the raw materials for the catalysts and found that the amount of catalyst affected the biodiesel yield. This study discussed the variation of biodiesel yield by increasing the catalyst dosage from 1 wt.% to 3 wt.%. The yield showed a rise with increasing catalyst at concentrations from 1 to 1.5 wt.% and peaked at 1.5 wt.% with a yield of approximately 95%. As the catalyst dosage continued to increase (>1.5 wt.%), the yield of biodiesel decreased. The decrease may be due to the side reaction of water in the feedstock with free fatty acids (FFA), i.e., saponification reaction, which produces soap and emulsion. The viscosity of the product gradually increases with the generation of soap and emulsion, which leads to a more difficult separation process and eventually affects the biodiesel yield.

Similar results were obtained in the study of Gupta & Rathod (2018, 169-178). The biodiesel yield increased from 72.18% to 96.07% when the catalyst addition was increased from 0.5 wt.% to 1.5 wt.%. However, the yield increase became small when the catalyst amount exceeded 1.5 wt.%. Gupta & Rathod (2018, 169-178) also mentioned that too much catalyst input increases the production cost of the whole process, which is detrimental to commercial production. Therefore, the amount of catalyst involved in the reaction has a significant impact on the final yield and cost of biodiesel. The optimum amount of eggshell catalyst can be determined as 1.5 wt.%.

3.3.2 Effect of methanol to waste cooking oil molar ratio

The molar ratio of methanol to WCO is another important factor affecting the yield of biodiesel in addition to the catalyst concentration. This is because the reaction of methanol with WCO is a reversible reaction and in order to keep the reaction always going in one direction during the production process, the molar ratio of methanol to WCO cannot follow the stoichiometric number in the equation. Finding a suitable molar ratio can promote a positive shift of the reaction equilibrium to obtain the best yield. (Gupta & Rathod 2018, 169-178.)

Tan et al. (2015, 58-70) conducted an experiment on molar ratios and biodiesel yields. This experiment measured the change in biodiesel yield as the methanol to WCO molar ratio ranged from 6:1 to 14:1. The biodiesel yield showed a rapid increase until the molar ratio of 10:1, with yields reaching approximately 95%. As the molar ratio continued to increase, the yield did not show significant changes and leveled off after experiencing small fluctuations. It can be predicted that even if the molar ratio continues to increase, the yield will not show an increase and, on the contrary, may trigger a decrease in biodiesel production. This experimental phenomenon was further explained by Tan et al. (2015, 58-70). Excess methanol can lead to a shift in equilibrium and thus harvest higher biodiesel yields. Therefore, higher molar ratios are usually used to facilitate the reaction between oil and alcohol. However, when the oil to alcohol ratio exceeds the optimum value, it can negatively affect the biodiesel yield. The addition of excess methanol has been shown to cause the separation of the ester and sugar alcohol phases to become sluggish. As a result, the final biodiesel yield will be affected. In addition, most of the glycerol will be dissolved in the excess methanol, which will inhibit the reaction, thus reversing the equilibrium and reducing the conversion rate. In addition, some glycerol will remain in the ester equivalents, which will further affect the final yield. Ghoreishi & Moein (2013, 24-31.) also mentioned that glycerol dissolved in the ester phase not only affects the yield but also increases the cost of downstream processing, which is not economical.

Niju, Meera, Begum & Anantharaman (2014, 702-706.) used waste eggshells as catalyst to convert waste oil recycled from school cafeterias into biodiesel. In this study, the best yield of 94.52% was obtained for biodiesel at a methanol to oil molar ratio of 12:1. Therefore, for eggshell catalyst the optimum molar ratio of methanol to WCO was set at 12:1.

3.3.3 Effect of reaction time

The appropriate reaction time is also an important factor to be determined. If the reaction time is too short, the reaction does not proceed completely, then will not be able to get a high yield. On the other hand, too long a reaction time is also not good. This is because the transesterification reaction is a reversible reaction. The hydrolysis reaction of fatty acid esters will increase with time. This will produce more fatty acid esters and water affecting the final yield. (Lu, Yuan, Li, Wang & Luo 2010, 283-287.) The study by Yin, Ma, You, Wang & Chang (2012, 320-325.) also mentioned that too long reaction time will promote the occurrence of inverse reaction. This will not only reduce the yield of biodiesel, but also lead to more saponification reactions.

According to the research of Tan et al. (2015, 58-70.), the optimal reaction times of two catalysts, chicken eggshell and ostrich eggshell, were compared. At the beginning of the reaction, the biodiesel yield of both catalysts increased with the reaction time. The maximum values were reached after 2 hours, i.e., 94% (eggshell) and 96% (ostrich eggshell). However, after 2 h, both of them showed different degrees of decrease. As mentioned earlier, this is the effect caused by the inverse reaction (hydrolysis reaction). Therefore, 2h could be the suitable reaction time.

3.3.4 Effect of reaction temperature

According to the research of Gupta& Rathod (2018, 169-178), the transesterification reaction is an endothermic reaction. Therefore, the reactants require a certain amount of energy in order to overcome the energy barrier and obtain the products. Hence, the reaction temperature is a non-negligible factor.

The relationship between biodiesel yield and reaction temperature was discussed by Tan et al. (2015, 58-70). The biodiesel yield kept increasing rapidly until 65°C. The highest yield, roughly 96%, was obtained at 65°C. Gupta, Yadav & Rathod (2015, 800-806) explain this phenomenon by stating that the increasing temperature reduces the viscosity of the mixture, which in turn reduces the diffusion resistance between the heterogeneous phases and the yield is increased. At the same time, the rise of temperature can build up the number of collisions between molecules, improve the reaction rate and promote the complete reaction.

However, after the temperature exceeds 65°C, the yield decreases with the increase in temperature (Tan et al. 2015, 58-70.). Maneerung, Kawi, Dai & Wang (2016, 487-497) provided an explanation for the decrease in biodiesel yield after the reaction temperature exceeded 65 °C. This is caused by the reaction temperature exceeding the boiling point of methanol (64.7 °C). Methanol vaporizes and forms bubbles, which remain in the gas phase and inhibit the reaction from proceeding, thus affecting the results.

Similar results were obtained in the study of Gupta & Rathod (2018, 169-178). The yield of biodiesel got the maximum value 93.1%, when the reaction temperature grew from 50 °C to 65 °C. But after the temperature exceeds 65 °C, the yield of biodiesel showed a rapid decline. At 70 °C, the yield was only about 85%. Therefore, 65 °C can be a suitable reaction temperature for eggshell catalyst.

3.3.5 Effect of speed of stirring

Lukić, Kesić, Zdujić & Skala (2016, 159-165) have mentioned that the transesterification process takes place in two systems, the liquid phase (methanol and oil) and the solid phase (eggshell catalyst). Since methanol and oil are incompatible with each other, it is difficult for this process to proceed smoothly without the aid of machine stirring. Stirring promotes contact between the reactants, breaks down the methanol droplets and increases the interfacial area with the oil. So, it is necessary to determine the speed of the stirrer.

Tan et al. (2015, 58-70) demonstrated the effect of stirring speed on biodiesel yield in their 2015 study. The stirring speed requirement for the egg eggshell and ostrich eggshell catalysts is almost equal at 250 rpm. In the work of Tan et al, the initial stirring speed was set to 50 rpm, and the initial yield of biodiesel was around 75% for both eggshell catalyst and ostrich eggshell catalyst. With the gradual increase of the stirring speed, the biodiesel yield from both catalysts was gradually increased to about 95%. However, after the stirring speed reached 250 rpm, both changes were not evident, which also meant that the continued increase did not lead to higher values. Therefore, 250 rpm is the optimum stirring rate.

According to the conclusions of Stamenković, Lazića, Todorović, Veljković & Skala (2007, 2688-2699), the yield of biodiesel is closely related to the stirring rate. At the beginning of the reaction, stirring promotes contact between reactants and also leads to the break-up of methanol droplets, which expands the interfacial area between oil and methanol. Therefore, the yield of biodiesel showed a rapid increase, which is similar to the conclusion obtained by Tan et al. in 2015. However, as the stirring speed continued to increase, the mixture involved in the reaction also gradually decreased and the production of biodiesel was delayed, which is the reason why the biodiesel yield was not increasing after the stirring speed exceeded the optimum value.

3.4 Potential improvements method

Production costs always determine whether a new process can be produced commercially on a large scale. The production of biodiesel is no exception. Choosing WCO reduces the cost of raw materials, but the cost of the process is equally important. In the production of biodiesel, the traditional mechanical stirring method requires a long reaction time, a large number of reactants, and a long interval between separation and purification. Scientist has developed process intensification (PI) technology as an alternative choice to traditional mechanical stirring method. PI technology is better due to shorter reaction time and elimination of mass transfer resistance. Among many kinds of PI technology, ultrasonic assisted is the most popular one. (Gaur et al. 2020; Sharma, Kodgire & Kachhwaha 2020.)

In ultrasonic assisted processing systems, the liquid medium undergoes a continuous process of expansion and recompression, which generates a large number of air bubbles. The bubbles contain not only solvent but also solute vapors and dissolved gases. At low frequencies of 20-40 kHz, the bubble rupture will release a large amount of energy. The reaction will also produce micro-jets, and the impact between the liquid media substantially enhances the mixing. The alcohols are emulsified in the oil phase and the phase boundaries are disrupted. The increasing mass and heat transfer rate create an emulsion with large surface availability which accelerates the reaction rate between the two phases. In addition, the rupture of the bubbles gives energy to the reactant molecules, thus reducing the activation energy. The physical and chemical effects provided at the same time contribute to the positive shift of the reaction equilibrium. (Sharma et al. 2020.)

As described below the ultrasound assisted system provides not only physical mixing but also the activation energy required for the transesterification reaction. This raises the reaction temperature, further promoting a complete reaction and increasing the reaction rate. When using egg-shell derived non-homogeneous catalysts, a liquid jet will be generated on the catalyst surface due to the uneven flow of liquid into the voids on the catalyst surface, which can reduce the size of the reactant droplets and facilitate the reaction. In general, ultrasonic assistance can facilitate the reaction better than conventional mechanical stirring. (Sherma et al. 2020.)

Furthermore, research from Chen, Shan, Shi & Yan (2014, 428-432) also proposed that the ultrasound-assisted system can help increase the recycle rate of the catalyst. That study conducted a set of comparative experiments where both experiments were performed with eggshell catalysts based on ostrich eggshells. The first experiment used an ultrasound-assisted system and the other group used conventional mechanical stirring. After eight transesterification cycles, the biodiesel produced using the ultrasound-assisted catalysts could still reach 80% yield, much higher than that using the mechanically stirred catalysts. Also, the study obtained the similar conclusion as Sharma et al. (2020) mentioned that ultrasound-assisted systems can reduce the response time. Compared to the 140 min reaction time of the mechanical stirring system, the ultrasound-assisted system required only 60 min.

4 WASTE COOKING OIL TO BIODIESEL IN CHINA FUTURE

Due to the dietary habits of people in China unlike other countries, a large amount of grease and waste oil is produced daily. The handling of WCOs is an issue that cannot ignore. In many large cities in China, about 500 million tons of WCO are produced each year, and if not properly disposed of, they not only end up in the city sewer system but are also reconstituted into edible oil by illegal WCO processing plants. This poses a serious threat to the environment and people's health. However, if WCO is used as a feedstock for biodiesel production, the primary threat will be transformed into wealth. The large amount of WCO will promote the development of biodiesel. (Zhao et al. 2021.)

Around 40-60% of WCO in China goes back to people's tables through illegal means every year. Although over 60% of WCO in Europe is also improperly disposed of, it is rarely returned to the people’s table. Therefore, using WCO to make biodiesel can not only promote sustainable development, solve the current situation of energy shortage in China, promote circular economy but also reduce environmental pollution, maintain food safety and citizens' health. (Zhao et al. 2021.)

This section will analyze the demand and cost of biodiesel in China. Attention will also be paid to the current WCO recovery methods and future recommendations. At the end, the future opportunities for converting WCO to biodiesel in China using waste eggshells as a catalyst are shown.

4.1 The opportunities of biodiesel in China future

As a new energy source, biodiesel can be widely used in the energy field. China's energy consumption is mainly supported by various fossil fuels. Biodiesel has been applied in some fields, but only as a supplementary fuel to diesel. (Xu, Li & Sun 2016, 318-330.)

The consumption of diesel in China's transportation industry is giant, accounting for roughly 62% of the total diesel consumption. Although the growth of diesel consumption has slowed down in recent years under the environmental protection policy of the Chinese government, the diesel crisis exhibited by many provinces is still a hidden problem for the national economy. Using biodiesel to replace diesel is considered a viable solution in the future, therefore, biodiesel has great potential in transportation. (Xu et al. 2016, 318-330.)

In electricity and heating areas, diesel is not widely used, mainly in the construction sector. However, the use of biodiesel in generators is still full of potential. Biodiesel is often applied in portable diesel generators due to the low oil quality requirements. This helps to save the high-quality diesel fuel for other applications where it is needed. (Xu et al. 2016, 318-330.)

In addition, agricultural machinery is also considered as a possible application area for biodiesel. The consumption of conventional diesel fuel in agricultural machinery has been stable, maintaining a consumption of 20 million tons per year. Considering that the requirement of oil quality for agricultural machinery will not be too strict, biodiesel is fully capable of undertaking this task. Although the diesel consumption of agricultural machinery is not much, nearly 20 million tons of biodiesel is still a considerable figure for China which is facing energy crisis. (Xu et al. 2016, 318-330.)

Biodiesel also faces good advantages in terms of national policies. In 2012, China has published the *Twelfth Five-year Plan for Renewable Energy Development* and the *Twelfth Five-year Plan for Bioenergy Development*. These two reports illustrated the development goals of biodiesel in China in the next five years. Before 2020, the national annual supply of biodiesel should reach 2 million tons. In the transportation sector, 15% of fossil fuels should be replaced by biodiesel. The implementation of national policies will help to increase the motivation of enterprises. Meanwhile, the Chinese government has also experimented with 33 cities by establishing special funding for nationwide resource recovery and bioenergy development in the future. (Zhang, Ozturk, Wang & Zhao 2014, 677-685.) Therefore, biodiesel has a good development prospect in China.

4.2 Opportunities for production costs in the future

The cost of production often determines whether new energy sources can be commercialized on a large scale. The total cost of one ton of biodiesel based on WCO is nearly 826.22 euros. And FIGURE 3 presents the proportion of each component. Collecting WCO occupies the main cost (83%), and the production process accounts for 16% of the total cost. The depreciation of the equipment of the biodiesel plant only accounts for 1%. (Zhao et al. 2021.)

As shown in FIGURE 3, the WCO recovery price is the main cost in the WCO collection component, which is about 94% of the total collection cost. Transportation costs account for about 6%. Among the production costs, the cost of transesterification process is the highest, accounting for 65% of the total production cost. The cost of the transesterification process includes the amount of methanol input, catalyst cost, electricity consumption, labor cost and other material inputs. In China, the transportation cost of biodiesel is around 36.65 euro/ton. The pre-treatment process of WCO only accounts for 8% of the production cost. (Zhao et al. 2021.)

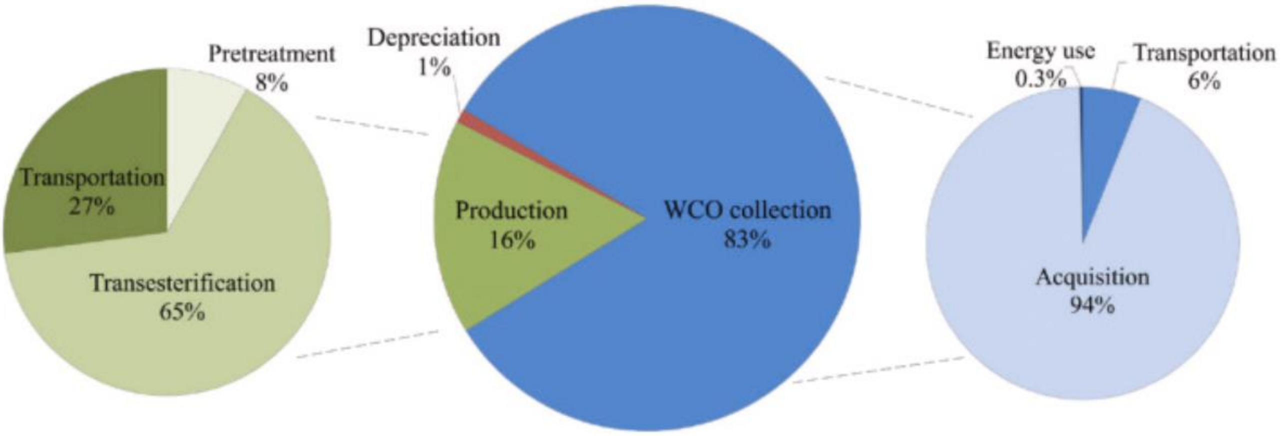

FIGURE 3 Production cost of WCO-based biodiesel (Zhao et al. 2021.)

The eggshell catalyst based on waste can reduce the cost to some extent, and the by-product glycerol can bring additional profit. However, in China, the total cost of conventional diesel is 629.39 euro/ton, which is significantly lower than that of biodiesel. Therefore, the economic disadvantage of WCO to produce biodiesel may hinder the development in China. (Zhao et al. 2021.)

4.3 Opportunities for WCO collection methods in the future

As mentioned earlier, in China, the collection of WCO is the most financially invested part of the entire production process. Currently, the use of waste cooking oil to make biodiesel in China involves the following groups: government, biodiesel plants, third party providers, illegals' plants and restaurants. Each local government sets the appropriate recycling policy according to the local situation. Biodiesel plants can recover WCO by themselves or entrust the third party to provide WCO, where the third-party provider is only responsible for collecting WCO and not for the quality of biodiesel. Restaurants are the main producers of WCO. Finally, illegal WCO processing plants are a noteworthy group. The imperfect policies, as well as high profits, lead some illegal elements to set up private plants and disrupt the supply chain of legitimate companies. (Zhang et al. 2014, 677-685.)

Next, this section will introduce each of the two recycling methods currently used in China. The first one is biodiesel enterprise take-back (BET). This model has no independent recycler, and the biodiesel plant buys directly from caterers and undertakes storage, transportation, and other operations. The representative cities are Ningbo, Suzhou and Lanzhou. The second type is called third party take-back (TPT). Contrary to the first one, the biodiesel plant is only responsible for processing and handling. The collection work is left to independent recyclers. The representative city is Nanjing. (Zhang et al. 2014, 677-685.)

4.3.1 Biodiesel enterprise take-back method

Although Suzhou, Ningbo and Lanzhou all use the BET approach, they are different from each other. According to Zhang et al.'s research, in Suzhou, government involvement is stronger than in the other two cities. The Suzhou government combats illegal plants by stopping illegal WCO transport vehicles. This facilitates restaurants seeking formal biodiesel plants. In addition, GPS devices and weighing equipment will be installed on vehicles transporting WCO. The managers will give penalties for deviation from the route or changes in fuel volume. Video surveillance is also in place for biodiesel processors to ensure that the production process is in compliance with regulations. In order to promote the development of biodiesel, Suzhou government has also introduced subsidy policies. A subsidy of 15.19 euro/ton was given to biodiesel companies and incentives were given to restaurants that took the initiative to provide WCO, which was due to the fact that illegal plants recycle at a higher price than biodiesel plants. Although the Suzhou government still lacks some incentives, such as lower sales tax on biodiesel, this has been superior to other cities' developments. (Zhang et al. 2014, 677-685.)

In Ningbo, the government issued a bill on WCO treatment to promote biodiesel development. The government promised to provide transportation means, i.e., the government leases and hires transportation vehicles to companies. At the same time, the government will also reduce the cost paid by restaurants by providing facilities dedicated to recycling WCO. Compared with Suzhou, there is no GPS and weighing system installed in the means of transportation, which will leave opportunities for illegal persons. On the other hand, the government's encouragement for the restaurant industry is inadequate. Restaurants not only get the centives, but also have to bear part of the transportation cost, which will undoubtedly increase the financial pressure of restaurants. (Zhang et al. 2014, 677-685.)

As for Lanzhou, although navigation tracking as well as weighing equipment is used in transportation, clear penalties are lacking. In addition, the subsidies promised by the government have not been granted on time, which has led to the slow development of Lanzhou. However, it is worthwhile for other cities to learn from the Lanzhou government's cooperation with domestic and foreign research institutions such as the Gansu Academy of Sciences to improve the yield rate. (Zhang et al. 2014, 677-685.)

4.3.2 Third party take-back method

Unlike other cities, Nanjing has adopted the TPT approach. In this approach, an independent company is responsible for recycling WCO. The government believes that the independent recycler can use its technical advantage to provide collection and transportation operations for biodiesel plants. (Zhang et al. 2014, 677-685.)

However, this approach also has significant drawbacks. Since the plant and the restaurant cannot communicate directly, it will lead to lower efficiency. Secondly, in order to seek high profit, the third party may exaggerate the cost of WCO or sell WCO to illegal plants. This will lead to insufficient supply of WCO, and biodiesel production cannot be carried out smoothly. Finally, the subsidy policy given by Nanjing government is for the amount of WCO recovery, not the amount of biodiesel production. People may artificially increase the weight of WCO for the subsidy money, such as adding food residue, which will not only affect the quality of biodiesel production, but also reduce the motivation of people. (Zhang et al. 2014, 677-685.)

TPT recycling method is also adopted in Japan and USA. However, unlike Nanjing, China, biodiesel companies do not have a high cost for WCO recycling but will receive financial subsidies. The degree of administration as well as technical regulations and support is much higher than Nanjing. Same as Nanjing, both countries do not give incentives to restaurants, which may be related to the fact that they have fewer illegal plants. In terms of recycling rates and corporate profits, both countries obtain better results than Chinese cities. (Zhang et al. 2014, 677-685.)

4.4 Future opportunities for eggshell catalysts in China

China is the world's largest producer of eggs. The country produced 56.6 billion in 2018, equivalent to forty percent of the global total. (Xinhua 2019.) In addition, China has the largest ostrich breeding population in Asia, with more than 100,000 animals per year. Ostrich eggs are the heaviest avian eggs in the world. They are around 15 cm long and 13 cm wide and weigh 20 times more than an egg, reaching 1.4 kg. (Chen et al. 2014, 428-432.) The mass of the eggshell is about 11% of the whole egg. In Taiwan, China, food processors produce about 13,000 metric tons eggshell per year. In the traditional sense, the waste from processors after the production of eggs or egg derivatives is useless. Usually, most of the waste eggshells are simply landfilled without treatment, which is a giant waste. But this is clearly unwise when one considers the odor produced by biodegradation, the organic matter attached to the shells and the substances contained in the shells themselves. The use of eggshells to make catalysts for biodiesel production can improve this situation and promote the recycling of biological resources. (Tsai et al. 2006, 488-493.)

China is also the world's second largest producer of solid waste after the United States. The Chinese government established a new waste separation program in March 2017, with the goal of reaching a 35% waste recycling rate in 46 major cities, including Shanghai, by 2020. Garbage collection efforts can boost recycling of solid waste, such as waste eggshells. (South China Morning Post 2019.)

Besides, Chung et al (2019) mentioned that catalysts for CaO derived from waste eggshells are less toxic to humans and terrestrial ecology in the preparation stage than the previously used KOH catalysts. The power requirements of the waste eggshell preparation process are also lower than those of the synthesis of pure KOH. This is because the preparation of spent eggshell catalysts is mainly a calcination process, whereas the synthesis of KOH involves a variety of chemicals. In addition, whatever use waste eggshell catalysts or conventional KOH catalysts have a certain environmental impact on the wastewater generated during the production process, but the impact of KOH catalysts is more severe.

4.5 Opportunities from value added by-products

As mentioned earlier, in the transesterification process, a large amount of glycerol is obtained in addition to biodiesel. Although the production of glycerol, to a certain extent, affects the purity of biodiesel if the separation is not complete. However, after certain treatment, glycerol can be sold in the market for profit. This is helpful to improve the overall production yield. (Kishor & Agrawal 2020.)

Compared to other feedstocks, WCO obtains the highest glycerol content of 76.6 %. Glycerol, a by-product obtained from the biodiesel production process, usually contains some impurities, such as unsaturated fatty acids or inorganic salts. After the separation, it should be purified. First, an acidification process using 98% sulfuric acid (H_2SO_4) is performed. This will divide the glycerol into three layers, with the unsaturated fatty acids at the top, accounting for roughly 20%, the acidified glycerol in the middle, around 70%, and the inorganic salts at the bottom. The separation is followed by an alkali treatment to neutralize the acidified glycerol, which can be done with sodium hydroxide (NaOH). After filtering out the sodium sulfate (Na_2SO_4) produced by the precipitation, pure glycerol is obtained by centrifugation. (Kishor & Agrawal 2020.)

5 CONCLUSIONS

Overall, the use of waste eggshells as a catalyst for biodiesel production from WCO is feasible. The use of waste eggshells as a catalyst can make the whole process more sustainable. Although the production of glycerol is unavoidable, the glycerol obtained after purification process can flow back to the market, which increases the additional profit of this process.

Like WCO, waste eggshells are widely available in people's daily life. Although it is less damaging to the environment than WCO, the large amount of waste eggshells also increases the workload of waste disposal. Therefore, using waste eggshells as catalyst can make the whole process more environmentally friendly. It is worth mentioning that waste eggshell catalyst is not a disposable product, it can be used many times, and in order to ensure the biodiesel yield, this study suggests that the number of cycles should be less than five. For the power supply of the whole production process, hydroelectricity can be tried, although the CaO catalyst derived from waste eggshells is also not good for human health, but it is much less than KOH. Of course, this does not mean that the subsequent wastewater treatment can let down the vigilance.

During the production process, it is important to pay attention to the FFA content, which is related to the success of obtaining biodiesel. In the transesterification process, the catalyst concentration was 1.5 wt.%, the molar ratio of methanol to oil was 12:1, the reaction time was 2 h, the reaction temperature was 65°C, and the stirring rate was recommended to be 250 rpm. Ultrasound assistance is a potential improvement option. With the help of ultrasound, the reaction time is drastically reduced, and the number of catalyst cycles is improved.

Environmental pollution from conventional fossil fuels as well as non-renewability also plague China. The biodiesel production method using WCO can not only alleviate the energy scarcity problem but also avoid the environmental pollution of WCO. China has the largest egg production in the world and the largest ostrich farming industry in Asia. From the perspective of raw materials, China has a great advantage. Moreover, the use of WCO to make biodiesel has already started in Suzhou and Nanjing, which will provide experience for large-scale production. However, the process also faces many challenges, such as competition from illegal companies, restaurants resisting cooperation for high profits, and lack of policy support.

In this thesis, the following suggestions for the future development in China from the perspectives of cost and feedstock collection. First, the government should publish strict penalties for factories that collect WCO illegally so that reprocessed WCO does not return to people's tables. The vehicles transporting WCO can be regulated by measures similar to those in Suzhou, i.e., adding GPS and weighing systems. The biodiesel plants can be subsidized according to the output of biodiesel in order to promote the construction of the plants. In addition, a complete production chain should be established, with biodiesel plants, glycerin plants and wastewater plants built together to reduce unnecessary capital spending and pollution. Finally, the local government can cooperate with universities or research institutes to provide the necessary technical support for the biodiesel plant.

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