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Case Study

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Waste to Biodiesel: A Preliminary Assessment for Saudi Arabia

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Abstract

This study presents a preliminary assessment of biodiesel production from waste sources available in the Kingdom of Saudi Arabia (KSA) for energy generation and solution for waste disposal issues. A case study was developed under three different scenarios: (S1) KSA population only in 2017, (S2) KSA population and pilgrims in 2017, and (S3) KSA population and pilgrims by 2030 using the fat fraction of the municipal solid waste. It was estimated that S1, S2, and S3 scenarios could produce around 1.08, 1.10 and 1.41 million tons of biodiesel with the energy potential of 43423, 43949 and 56493 TJ respectively. Furthermore, annual savings of US $55.89, 56.56 and 72.71 million can be generated from landfill diversion of food waste and added to the country's economy. However, there are challenges in commercialization of waste to biodiesel facilities in KSA, including waste collection and separation, impurities, reactor design and biodiesel quality.

Keywords: Biodiesel; Waste sources; Fuel; Energy; Transesterification

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1. Introduction

The over-exploitation of natural resources has increased the global concerns for anthropogenic climate change and security of energy, food, and water (Nizami et al., 2017). This has led to a move towards exploring eco-friendly and renewable fuels. Consequently, biodiesel has emerged as a promising fuel for the future, especially to substitute fossil oil in the transport sector (Nizami et al., 2016). Biodiesel consists of fatty acid methyl esters (FAME) (C_{16}-C_{18}) and can be produced from various plant or animal based biological feedstocks in a process known as transesterification (Ouda et al., 2016).

A wide range of feedstocks (more than 350 oil-bearing crops) have been found worldwide for the production of biodiesel (Oh et al., 2012; Demirbas, 2009). Therefore, a variety of oil stocks has been utilized experimentally to produce biodiesel. These include virgin oil feedstock such as rapeseed oil, soybean oil, sunflower oil, palm oil, mustard oil, jojoba oil, tung oil, rubber oil, cotton seed oil, Neem oil, Nahor oil, Karanja oil, Jatropha oil, Pongamia oil and rice bran oils. Oils from tallow, lard, yellow grease, chicken fat and by-products of fatty acids from fish oil and flaxseed oils are also used (Leung et al., 2010). Moreover, oils from algae and microalgae have been utilized in the last decade with better yields and reduced prices. In general, the primary feedstock categories around the world are classified into edible vegetable oil, non-edible vegetable oil, waste or recycled oil and animal fats (Atabani et al., 2013). A comparative summary of the biodiesel properties produced from non-food feedstocks or waste sources in comparison to petrodiesel is shown in Table 1.

The choice of feedstock for biodiesel production mainly depends on environmental conditions, agricultural practices, soil availability and characteristics and geographical locations, which vary from country to country (Nizami et al., 2017). For instance, palm oil is predominant in Malaysia due to favorable soil conditions, whereas soybean oil is dominant in the United States (US) due to weather conditions as well as utility value (Huang et al., 2010). The feedstock used for biodiesel production is a critical parameter in estimating the total cost of biodiesel production and revenue. Since the running of Rudolf Diesel's first engine on peanut oil in 1893, the availability of the cheap feedstocks in biodiesel production has been a chronic issue. It is estimated that up to 75% of the overall biodiesel production cost arises from the choice of raw material. Therefore, various novel approaches such as the use of different non-food feedstocks, novel heterogeneous solid-based catalysts and carbon supported feedstocks are being explored to reduce the overall cost of biodiesel production (Borges and Díaz, 2012).

The economic production of biodiesel is still in its infancy because of process economics, technical challenges and regulatory barriers (Martín and Grossmann, 2014). In 2012, about 12% of the world's sources of edible vegetable oil was used in the production of biodiesel that affected the prices of food, animal feed and edible oils across the globe, especially in developing countries (Demirbas, 2009). Therefore, the production of biodiesel from food feedstocks such as edible oils are 1.5 to 3 times more expensive than petrodiesel and cover 60 to 80% of the total production cost (Atabani et al., 2013). In addition, labor facility, methanol, and catalyst, base-stock, seasonal changes in feedstock production and geographical area affect the overall production cost of biodiesel. Nonetheless, in developing countries, biodiesel from food sources is increasing the public fear of creating food shortage and poverty (Martín and Grossmann, 2014).

Biodiesel from non-food sources such as sewage sludge, waste cooking oil (WCO), microalgae and animal fat wastes along with non-edible oil seeds such as Jatropha, Pongamia, Neem, Camelina, and Soapberries has gained significant attention due to positive energy balance and economic and environmental values as compared to both petrodiesel and conventional feedstock based biodiesel (Rathore et al., 2016). Moreover, a lot of non-food sources, as mentioned above are classified as wastes and would provide enormous economic and environmental benefits if used for biodiesel production. Biodiesel from such non-food feedstocks is of high quality and can be directly used in diesel engines or after mixing with petrodiesel (Nizami et al., 2015).

In the Kingdom of Saudi Arabia (KSA) and Gulf region, the rapid growth in population, urbanization and industrial activity have resulted in significant demands of energy along with generation of municipal and industrial waste (Ouda et al., 2016). The current electricity generating capacity of KSA is about 55 GW that is projected to cross 120 GW by 2032 with the current increase of 8% per year (Nizami et al., 2015). More than 50% of the electricity is only consumed for residential purposes such as air-conditioning (Nizami et al., 2017). Every year, more than 15 million tons of municipal solid waste (MSW) is generated in KSA, which after partial recycling (up to 15%) end up in the dumpsites or landfills without energy recovery (Ouda et al., 2016). This results in a significant environmental and economic loss which is added to the country's economy and the public by having no waste to energy (WTE) or efficient recycling schemes. Recently, the KSA's government has launched a new policy of Vision 2030 with a determination to enable circular economy in the country by generating renewable energy from indigenous sources such as the wind, solar, geothermal and waste (Vision2030, 2016).

This study, a first of its kind for this region, aims to provide a preliminary assessment of the biodiesel production from the waste sources available in KSA as a mean of renewable energy generation and a solution for waste disposal issues. A new set of data is provided from waste and non-food sources such as sewage sludge, WCO, animal fat wastes and agricultural residue of KSA and their utilization in biodiesel production. The cost-reducing scenarios and challenges from the waste and non-food sources based biodiesel are also presented in detail. The findings of this study would, therefore, facilitate the scientific knowledge in the biodiesel production design, site selection, process optimisation, and equipment evaluation in the KSA and Gulf region to support the concept of circular economy.

3. Methodology

3.1 Studied region – KSA

There is a considerable potential for developing waste to biodiesel facilities in KSA, with tremendous economic and environmental benefits that would play a significant role in achieving circular economy in the country. A case study has been developed in this context to visualize a fraction, but enormous, benefits of the waste to biodiesel by utilizing only fat fractions (13.03%) of total food waste (50.60%) in the country. Three scenarios were developed for waste to biodiesel facilities in KSA such as (S1) KSA population only in 2017, (S2) KSA population and pilgrims in 2017, (S3) KSA population and pilgrims as planned by 2030.

The case study was made on three scenarios because of the special circumstances of KSA. This is the only country in the world that facilitates millions of pilgrims every year from all over the world (Nizami et al., 2017). The number of pilgrims will increase several folds in coming years to reach up to 30 million per year due to the multi-billion dollars expansion projects of the two Holy Mosques and the government's new policy of Vision 2030 (Vision2030, 2016). This creates a number of serious challenges for the local authorities to preserve the health and safety of visitors as well as providing them with exceptional facilities to perform religious rituals within a limited time and space (Nizami et al., 2017). One of the distinct challenges in this regard will be the generation of the massive amount of waste by the visitors.

3.2 Case study assumptions under different scenarios

The total amounts of generated MSW, fat fractions and biodiesel production potential through transesterification process have been estimated. The total energy potential of biodiesel in TJ using its standard HHV value of 40.17 MJ/kg was also calculated. In scenario 1 (S1), the total MSW generated by KSA population only in 2017 was estimated to be around 16.73 million tons based on the estimated 2017 population of 32.74 million and waste generation rate of 1.4 kg per capita per day. The food waste was considered to be 50.6% of total generated MSW, and 13.03% of food waste was assumed to be the fats fraction (Nizami et al., 2015). A conversion efficiency of 98% for fat fraction into biodiesel through transesterification process was considered (Shahzad et al., 2017). Biodiesel is obtained from catalysis of triglyceride with alcohol and a catalyst such as KOH or NaOH or with supercritical methanol without a catalyst (Demirbas, 2009). The final ester product such as FAME is produced when methanol is used as alcohol. However, there are biodiesels produced as ethyl esters, also called fatty acid ethyl ester (FAEE), which are more expensive than ethanol in comparison to methanol in the general market. In addition, other higher alcohols such as 2-propanol and 1-butanol are used for the production of biodiesels (Oh et al., 2012). Several factors such as mole ratio (alcohol to oil), reaction temperature and time, type and dose of catalyst, free fatty acids (FFA) and the moisture contents in feedstocks significantly affect the yield of biodiesel. For example, water contamination affects the functioning of biodiesel and results in low quantities and immiscibility in biodiesel. In explicit terms, water causes corrosion and smoke, reduces the heat of combustion, reduces fuel power and freezes to form ice crystals and to clog or gel the fuel. However, according to Atadashi et al. (2012), the use of methanol without catalyst reduces the water problem in transesterification process, mainly when using vegetable oil feedstocks.

The total energy potential of biodiesel under all three scenarios was estimated based on its HHV of 40.17 MJ/kg (GREET, 2010). The savings from landfill diversion of food waste was calculated using standard gate fee of around US $50 in KSA (Ouda et al., 2016; Nizami et al., 2017). In scenario 2 (S2), the MSW generated by Hajj pilgrims was estimated based on the assumption that each pilgrim will stay for an average period of 7 days and will produce on average 2.2 kg waste per day. In 2017 Hajj period, around 2.5 million pilgrims are expected to visit KSA due to completion of two Holy Mosques expansion projects (Nizami et al., 2017; Shahzad et al., 2017). The MSW generated by Umrah pilgrims was estimated based on the assumption that each Umrah pilgrim will stay for an average period of 10 days and will produce on average 2.05 kg waste per day. About 8 million Umrah pilgrims are expected to be visiting during 2017. The total MSW for S2 would be equal to MSW of S1 plus MSW generated by Hajj and Umrah pilgrims.

In scenario 3 (S3), it was assumed that the generation rate of MSW would increase with the current growth rate of KSA population (Nizami et al., 2017; Shahzad et al., 2017). It was estimated that by 2030, a total MSW of 21.07 million tons would be produced in KSA using the same generation rate of 1.4 kg per capita per day. In S3, the MSW generated by pilgrims was estimated based on two factors. In the first factor, the MSW produced by Hajj pilgrims was estimated based on the assumption that each pilgrim will stay for an average period of 7 days and will produce on average 2.2 kg waste per day. In 2030 Hajj period, around 5 million pilgrims are expected to visit KSA, as planned in the governmental policy of Vision 2030 (Vision2030, 2016). In the second factor, the MSW generated by Umrah pilgrims was estimated based on the assumption that each Umrah pilgrim will stay for an average period of 10 days and will produce on average 2.05 kg waste per day. Around 30 million Umrah pilgrims are expected to be visiting during 2030. The total MSW for S3 would be equal to the total MSW as estimated based on KSA population plus MSW generated by total Hajj and Umrah pilgrims by 2030 (Vision2030, 2016).

The estimations made in this case study were based on minimum values for a number of pilgrims, average stay per pilgrim, waste generated and so on, since there are very little information and accurate data available in this regard. However, the authors believe that the actual values would mostly be higher than used in this study and that would have a further positive significant impact on economic and environmental benefits of developing waste to biodiesel facilities in KSA.

3.3 Potential waste sources for biodiesel in KSA

3.3.1 Biodiesel from sewage sludge

Sewage sludge is derived from wastewater treatment process and mainly consist of lipids, proteins, sugars, detergents, phenols and organometallic compounds (Demirbas, 2009). Moreover, lipids in the form of greases, oils, fats and free fatty acids (FFAs) are extracted from municipal, domestic and industrial sludge along with some toxic and hazardous organic and inorganic pollutants. The sewage sludge is a non-food and readily available source for inexpensive lipids to produce biodiesel in comparison to biodiesel produced from edible vegetable oils. In recent years, sewage sludge has been extensively examined for their potential role in biodiesel production (Tran-Nguyen et al., 2015).

In KSA, about 12,000 industries are working in various sectors that along with municipal generate tremendous quantities of waste sludge on a daily basis. For instance, only in Jeddah city of KSA during 2013, about 120 tons of sludge was produced every day on dry solid basis. Whereas in Riyadh, about 200 dry tons of sludge was produced every day during 2013. It is estimated that total amounts of sludge in the KSA would reach up to 1.6 and 1.8 thousand tons per day on the dry solid basis in 2020 and 2025 respectively (SAWEA, 2013). Typically, sewage sludge contains organic matter (42-59%), organic carbon (20-40%), ash (34-44%), oxygen (18-22%), nitrogen (0.4-0.5%), hydrogen (0.4-0.5%) and mineral matter (11-15%) (Demirbas, 2009). Therefore, waste sludge can be a significant source of massive quantities of biodiesel in KSA to substitute conventional fuels and meet the future energy demands of the country (Nizami et al., 2017).

Biodiesel can be produced from sewage sludge by two different methods such as catalyzed transesterification and supercritical methanol transesterification (Demirbas, 2009). Both acid and base catalysts can be used with their advantages and disadvantages in the catalyzed transesterification processes. Sewage sludge is subjected to a pretreatment before lipid extraction. The lipids fraction in the sewage sludge is the composite of lipids, greases, and fats. Once this lipids composite is extracted, using various organic solvents, is converted into biodiesel through transesterification. Whereas, the secondary sludge or activated sludge is extracted after the removal of dissolved organic compounds and some nutrients in the sewage sludge (Kargbo, 2010). The yield of biodiesel obtained from primary sludge is higher than the secondary sludge. However, the extraction of lipids from sewage sludge is still a limiting factor in the commercial application of waste to biodiesel (Urrutia et al., 2016). A flow diagram of biodiesel production from the sewage sludge is shown in Figure 1.

Alkali-catalyzed and supercritical methanol transesterifications are promising methods for producing biodiesel from sewage sludge. Sludge with lipids or FFAs greater than 1%, first undergoes acid catalytic and then base catalytic transesterification to prevent soap formation in the reaction medium (Kargbo, 2010). In non-catalytic supercritical methanol transesterification, the dielectric constant of methanol decreases in supercritical conditions. As a result, the oil and methanol are mixed to form a single homogeneous phase to solve the problems of two-phase catalytic transesterifications (Urrutia et al., 2016).

3.3.2 Biodiesel from waste cooking oil (WCO)

The WCO or waste vegetable oil (WVO) or waste frying oil (WFO) is another promising feedstock for biodiesel production. Due to its high water and FFA content, the catalytic transesterification is a preferred method for converting waste or used oils into biodiesel by recycling polyesters into individual monomers (Demirbas, 2009). It is a chemical reaction by which WCO is reacted with short chain alcohols like methanol or ethanol under the influence of a catalyst. In addition, glycerol, soap and excess alcohol are generated besides biodiesel, which is removed by various standard methods. If the WCO contains high acid, then water is removed separately before using in transesterification. For this, different catalysts are used to achieve low moisture content and light color biodiesel from WCO (Tropecêlo et al., 2016). A flow diagram of biodiesel production from WCO is shown in Figure 1.

The cost of obtaining WCO is around 2.5 to 3.5 times lower than using edible vegetable oils. Therefore, the biodiesel produced by used/recycled oils may lower the prices of biodiesel and decrease the environmental overburden coming from the disposal of WCO (El Sabagh et al., 2011). Many researchers have studied the production of biodiesel from WCO at different process conditions and catalysts. Leung et al. (2010) reported a biodiesel yield of 94.6% from WCO at 60 °C, 20 min, 600 rpm, methanol to oil ratio of 7:1, with 1.1 wt% NaOH catalyst. Similarly, yields of 92.05 and 89.9% were achieved by Atapour et al. (2014) and Meng et al. (2008) using NaOH (0.72 and 1.0 wt%) catalysts at process conditions of 65 and 50 °C, 45 and 90 min, and methanol to oil ratio of 9:1 and 6:1 respectively. Buasri et al. (2012), used other catalysts such as KOH and CaO and reported biodiesel yields of 86.3 and 94% from WCO at 60 °C, 120 and 480 min, methanol to oil ratio of 25:1, respectively. A very high biodiesel yield of 98% was reported by Jacobson et al. (2008) from WCO using a combination of Zinc stearate/ Si catalyst (3.0 wt%) at 200 °C, 600 min, 600 rpm and methanol to oil ratio of 18:1.

The prices of biodiesel from WCO may vary from region to region, geographic and agricultural conditions and the raw materials collection and distribution facilities along with the feedstock quality and availability around the year (Tropecêlo et al., 2016). A significant fraction of the KSA's MSW is consist of WCO from households and restaurants. Every year around 15 million tons of MSW is generated with food waste as being the most abundant waste stream, which is more than 50% of the total collected MSW in the country (Ouda et al., 2016). It is estimated that around 13% of the total collected food waste further consists of fats contents in the form of edible fats and WCO (Nizami et al., 2015). Therefore, WCO can be a promising source of biodiesel production for generating renewable energy or used as a transport fuel besides solving the local waste disposal issues (Nizami et al., 2017).

3.3.3 Biodiesel from waste animal fats

Animal fats are obtained from beef tallow, poultry fat, fish oils and yellow greases. The biodiesel production from different types of waste animal fats is possible by following a standard method of EN 14214 (EN, 2003). However, biodiesel is mainly produced from two kinds of waste animal fats such as tallow and poultry fat. The general characteristics of animal fats tallow and poultry include kinematic viscosity of methyl ester 3.1 and 3.3 (mm^2/s at 40 °C), kinematic viscosity of fat 46.0 and 41.0 (mm^2/s at 40 °C), iodine value of fat 45 and 77 (g/ 100g), acid value of fat 1.1 and 0.6 (mg KOH/g fuel) respectively (Demirbas 2009). Moreover, other features of tallow and poultry include stearic acid content, myristic acid content, oleic acid content, linolenic acid content, linoleic acid content, palmitic acid content with values of 16.4 and 6, 8.5, 40.5 and 47, 0.2 and 1.4, 3.4 and 15.6, 31 and 30, respectively (Demirbas 2009).

The values of kinematic or dynamic viscosity and the presence of saturated fatty acid in animal fats are higher in comparison to vegetable oils. Thus, the biodiesel obtained by animal fats has higher cetane number than biodiesel produced by vegetable oils (Bala, 2005). A flow diagram of biodiesel production from the animal fats is shown in Figure 1. In KSA, during 2007's Hajj period, around 700 thousand goats were slaughtered in performing religious rituals, whereas this number has increased almost four times (2.5 million animals) in 2014's

Hajj period (Nizami et al., 2015; Nizami et al., 2017). According to Singh (2013), 12% waste is produced per body weight of sheep and goat, whereas 38% waste is produced per body weight of cattle. The animal waste in KSA mainly consists of the rumen, blood, stomach, intestine, tallow, and fats (Shahzad et al., 2017).

3.3.4 Biodiesel from agricultural wastes

Several agricultural wastes can be used as a promising feedstock for biodiesel production. The examples of such waste are tea seed, tobacco seed, tomato seed, linseed, bay laurel leaves and fruits and cherry seed along with some non-conventional seed oils such as corn germ oil, rice bran oil, and cherry laurel seed oil and date palm seed (Demirbas, 2009). The seed oils that have high FFAs are used in two-steps process of biodiesel production. In the first step, the catalytic acid esterification is carried out to reduce the FFAs contents to less than 2%. In the second stage, alkali catalytic transesterification process is used to convert the products of the first step into biodiesel. Currently, in the world, there are abundant resources of tobacco seed, tea seed and corn germ for producing low-cost biodiesel (Oh et al., 2012).

In KSA, according to Al-Abdoulhadi et al. (2011), around 23 million palm trees are present that produce around 780 thousand tons of dates annually. Therefore, the country is one of the primary producers of date fruits in the world. Sadik et al. (2010) have estimated that more than 440 million tons of agriculture waste are generated every year in the country. The waste of palm trees and dates seeds are the largest waste stream among the agricultural residues. Currently, this waste is mostly incinerated or disposed of without any treatment or used in animal feed. The date seeds can be a potential source of biodiesel in the country using transesterification of the extracted date seed oils by methanol/KOH mixture. However, the agricultural waste has to be pretreated before being used in the transesterification process (Demirbas, 2009).

3.3.5 Biodiesel from non-edible oils and wood oil

The non-edible oils are the low cost, readily available, and portable and renewable source of biodiesel production with low sulfur contents. However, the primary disadvantages in using non-edible oils are the high contents of FFAs and water that increase the overall production cost of biodiesel (Banković-Ilić et al., 2012). There are many sources of non-edible oils such as jatropha tree (*Jatropha curcas*), Karanja (*Pongamia pinnata*), Mahua (*Madhuca indica*), castor bean seed (*Ricinus communis*), Neem (*Azadirachta indica*), tea seed, tomato seed, rubber seed (*Hevea brasiliensis*), tobacco seed (*Nicotiana tabacum*), corn germ and rice bran, which can be used as a potential feedstock for biodiesel production (Thangaraj et al., 2014).

In recent years, the biodiesel from non-conventional oilseed plants has gained significant attention (Thangaraj et al., 2014). In countries like KSA, the non-edible plant oils are readily available and are very economical as compared to edible plant oils. However, most of these non-edible oils can pose a potential risk to human health due to the presence of some toxic elements. Moreover, the non-vegetable oil with more than 1% FFAs undergoes in the process of acid-catalyzed esterification (Chai et al., 2014). In the process of biodiesel production by non-edible oils, sulfuric, hydrochloric and sulfonic acids are mainly used as acid catalysts (Martín and Grossmann, 2014).

Biodiesel from wood oil can be produced from 11% of oil extracted from freshly cut wood through supercritical solvent extraction method and 2.6% of fatty acids from the extract. Kraft process is used to obtain tall oil from wood pulp along with resin acids, fatty acids, and neutral compounds or unsaponifiable (Oh et al., 2012). In addition, biodiesel can be produced from tall crude oil in a single step esterification process with yields more than 94%. The typical chemical composition of tall oil from a coniferous wood showed 49% resin acids, 32% fatty acids like oleic, linoleic and linolenic acids and 19% unsaponifiable. The crude tall oil composition varies significantly according to wood species (Martín and Grossmann, 2014). The massive quantities of waste wood of palm trees in KSA could be a promising source of biodiesel production along with value-added products.

3.3.6 Biodiesel from algae oil

Algae are the fastest growing plants having most rapid photosynthesis due to a different carbon dioxide (CO_2) reaction mechanism as compared to other plants. Algae grow mainly in open ponds, photo-bioreactors and closed and hybrid systems (Makareviciene et al., 2014). In comparison to estate land plants, microalgae consume less water. However, the farming of microalgae cost much more than conventional farming. Microalgae are a promising source of biodiesel that would be deployed on an extensive scale in the near future. Microalgae are an economical option for biodiesel production due to their radial availability and low cost. The capital and operating cost of open ponds for microalgae growth are lower than those of other systems (Chisti, 2007). Many researchers have reported that biodiesel obtained from microalgae would be more efficient than other methods of biodiesel production (Tüccar et al., 2015). A simple flow diagram of algal biodiesel production is shown in Figure 1. The different species of algae contain between 2 to 40% of oils by body weight. The algae oils are extracted through Soxhlet extraction method using hexane for 18 hours. Characteristics wise, the biodiesel from algae oil is not significantly different from biodiesel produced from vegetable oils. However, the production yield of oil per acre basis is 200 times higher in microalgae than any vegetable oils, as the photosynthesis takes place very fast in microalgae (Sheehan et al., 1998).

4. Results and Discussion

4.1 Energy generation and economic benefits of waste to biodiesel facilities in KSA

The amounts of MSW and fat fractions, biodiesel production from fat fractions, energy potential and the economic benefits for all three scenarios were studied. The total amounts of annual MSW were estimated to be 16.73, 16.93 and 21.77 million tons per year for S1, S2 and S3 respectively. Similarly, the food waste fractions were estimated to be 8.47, 8.57 and 11.01 million tons per year and fat fractions of 1.10, 1.12 and 1.44 million tons per year respectively (Figure 2). If all of this fat waste is converted into waste to biodiesel facilities through transesterification process with process efficiency of 98% and utilizing suitable catalysts, 1.08, 1.09 and 1.41 million tons of biodiesel per year could be produced. This biodiesel holds the total energy potential of around 43423, 43949 and 56493 TJ per year from S1, S2 and S3 respectively (Figure 2).

There are tremendous economic benefits of waste to biodiesel plants if developed in KSA, including direct savings of millions of US $ as well as building various small to medium scale businesses and creating thousands of jobs every year, which are critical elements of developing a circular economy in the country. An example of economic benefits in this case study for producing biodiesel from only one source of fat fraction of MSW is presented. It has been estimated that savings of around US $55.89, 56.56 and 72.71 million can be generated, based on standard gate fee of US $50 in KSA, from landfill diversion of food waste and added to the country's economy. Moreover, the economic benefits, from biodiesel selling or blending with conventional fuels or using for long-range transportations (trucks), in millions of US $ could also be added to the economy. However, this requires a detailed life cycle assessment (LCA) study considering detailed costs of biodiesel production, all byproducts such as exhaust cakes, and glycerol, all emissions and industrial energetic and resources expenditures like extraction with solvents for biodiesel production.

The comparison of three scenarios showed not only the impact of pilgrims on waste generation but also its potential to be used for producing biodiesel to get substantial economic and environmental benefits (Figure 2). The impact of S2 in comparison to S1 is only around 1% since the current number of pilgrims are very low compared to KSA population. However, S3 has a significant impact of around 30% in comparison to S1, mainly because of the significant increase in number of pilgrims from annual 8 million up to 30 million as planned in vision 2030 as well as a projected increase in the KSA population and MSW generated by 2030 (Vision2030, 2016). For example, 1.41 million tons of biodiesel could be produced in S3 as compared to 1.08 million tons in S1. Similarly, 56493 TJ of energy can be obtained from biodiesel in S3 as compared to 43423 TJ in S1. Furthermore, savings of US $72.71 million could be made in S3 as compared to US $55.89 million in S1, respectively.

4.2 Advantages and challenges of using biodiesel in KSA

Biodiesel has many advantages as an alternative fuel to petrodiesel, including availability, renewability, higher combustion efficiency, environmental friendliness and higher biodegradability. In addition, biodiesel has a higher cetane number than petrodiesel. Leung et al. (2010) have observed that biodiesel blended with petrodiesel provides enhanced performance of engines in comparison to the pure 100% biodiesel. The various properties of biodiesel produced from non-food feedstocks in comparison to petrodiesel are shown in Table 1. It is noticeable that the biodiesel has a high flash point that makes it even safer to transport or handle. In addition, the lubricity of biodiesel is higher than petrodiesel due to a higher viscosity, and this reduces engine wear and extends the overall engine performance and life (Subramaniam et al., 2013).

Despite the numerous benefits of biodiesel, there are some challenges such as constraints on the availability of agricultural feedstocks, especially in KSA due to warm and arid climatic conditions, inferior storage over prolonged periods and oxidative stability, lower energy contents, higher NOx emissions and difficulty in low-temperature operations (Misra and Murthy, 2011). However, the exhaust emissions when using biodiesel engines result in reduced emissions of unburned hydrocarbons, carbon monoxide (CO), sulfates, polycyclic aromatic hydrocarbons (PAHs), nitrated polycyclic aromatic hydrocarbons and particulate matter (PMs) (Borges and Díaz, 2012). According to Sheehan et al. (1998), the net CO_2 emissions and the effect of biodiesel blends on the emissions of a bus showed 78.45% reduction in CO_2 emissions when pure biodiesel was used as compared to petrodiesel. Similarly, when biodiesel was blended with B20, the net CO_2 emissions reduction was 15.66%. The most disadvantage pollutant is NOx emissions that are higher in biodiesel than in petrodiesel. Bhale et al. (2009) studied the effect of different blending of mahua methyl ester (MME) with ethanol and results showed that blending 80% of biodiesel with 20% of ethanol reduces the amount of NOx emissions, as compared to the pure product. This phenomenon is due to the higher value of latent heat that decrease the temperature, thus reducing NOx emissions. The other limitations in the commercialization of biodiesel are poor cold flow behavior, which might be not the case for KSA as the average temperature in the country remains above 25 ^{o}C throughout the year.

Following are the key challenges in the use of waste and non-food feedstocks for biodiesel production.

- Pre-treatment of feedstocks like WCO is not economical if contains more than 3.0% of FFA and more than 0.5% water
- Limitations of biodiesel quality, especially the poor cold flow properties and low oxidative stability
- Sludge cost varies with the choice of pretreatment and treatment method of wastewater
- Engineering challenges in reactor type and design for accelerating the biodiesel production
- Yield of secondary sludge is lower than primary sludge
- Costly methods and issues of waste collection and separation before used as feedstock
- Additional costs by filtration, centrifugation and drying producers
- Soap formation limits the separation of glycerol

4.3 Blending of biodiesel – a promising fuel market in KSA

Blending is a recognized method for enhancing the biodiesel properties. The physical properties of the biodiesel that affect its efficiency in diesel engines can be enhanced by mixing different portions of biodiesel with other fuels such as kerosene, ethanol, and petrodiesel (Misra and Murthy, 2011). Although the blending is conventionally based on the composition of biodiesel and petrodiesel, there have been recent studies with blends from different fuels and use of additives for improving the overall fuel properties of biodiesel. Bhale et al. (2009) studied mahua methyl ester (MME) blended with 20% ethanol and observed that the cloud point was reduced from 18 to 8 ^{o}C and pour point from 7 to -4 ^{o}C. Similarly, when MME was blended with 20% kerosene, the cloud point was reduced to 5 ^{o}C and pour point to -8 ^{o}C.

The pour point depressants (PPD) are crystal growth inhibitors used to reduce the pour point of biodiesel. The pour point of MME was found to be reduced from 7 ^{o}C to -5 ^{o}C with an additive of 2.0% of Lubrizol. Kinematic viscosity is another essential property of biodiesel. The kinematic viscosity of MME was found to increase from 1.6 times of diesel when the temperature was decreased from 40 to 25 ^{o}C. This phenomenon was due to a crystallization of the saturated FAME components of the biodiesel at an earlier temperature. Fuels with high flash point and fire point are safer for storage and transport due to less volatile nature. Bhale et al. (2009) looked at the effect of blending ethanol, kerosene, and petrodiesel with MME. They have observed that although MME shows a higher flash point and fire point than petrodiesel, when blended with ethanol and kerosene these properties are found to be reduced, indicating that blending is a critical phenomenon for biodiesel.

The CFPP decreases with an increase of double bonds and increases with chain carbon length. The reactivity towards oxidation also depends on the structure of fatty acid in biodiesel fuel. The relation between oxidation stability and CFPP was investigated by Zuleta et al. (2012). A different binary of obtained biodiesel from palm, sacha-inchi, jatropha and castor oil was used to investigate their CFPP and oxidation stability. They observed that the best performing binary system was 75% Jatropha and 25% castor oil are showing an induction time of 7.56 hours and a CFPP reduction to -12 ^{o}C. Bezergianni and Chrysikou (2012) have examined the properties of FAME produced from WCO and white diesel and compared the storage conditions based on their induction periods. They observed that the cloud point, CFPP and pour point do not change for white diesel on storage at room temperature even after a year, there was no appreciable water formation and no change in the flash point, making it a useful option in the biodiesel industry in KSA. Similarly, blends of biodiesel with other conventional fuel showed better fuel properties than the neat ones in several of the virgin oil feedstocks that showed difficulties in the earlier studies (Šimáček et al., 2011).

4.4 The variations in the quality of biodiesel

The produced biodiesel from any feedstock or reaction has to be processed and purified to meet the international standards in order to ensure better engine performance (Oh et al., 2012). For instance, vegetable oils have a high viscosity that has led to the poor atomization of the fuel causing deposits and coking of injectors, combustion in chamber and valves of engines (Borges and Díaz, 2012). Whereas, biodiesel produced from WCO showed better engine performance with better viscosity-related properties and reduced emissions without compromising the quality of the biodiesel. Similarly, the Neem, a multi-purpose evergreen tree is utilized for biodiesel production and has shown an increase in the thermal brake efficiency of around 1.5% and improvement in exhaust emissions, especially for carbon monoxide (CO) and hydrocarbons (Subramaniam et al., 2013).

In individual European countries, the biodiesel standards differ due to varying temperature requirements. The biodiesel standards of some of the other countries are China (GB/T 20828-2007), Germany (DIN V 51606) and India (IS 15607) (Sarin et al., 2007). Many researchers have extensively studied the properties of biodiesel to understand their effect on the performance of the engines (Subramaniam et al., 2013). The comparison of different features for biodiesel (B100) is based on the most common standards around the world, which is American Society for Testing and Materials and European Standard (EN, 2009).

Viscosity is a critical parameter that influences the biodiesel compositions and performance in compression-ignition engines. An increase in viscosity affects the fluidity of the fuel and causes low volatility. According to Quinchia et al. (2012), the viscosity is found to decrease with an increase in the oil temperature. Similarly, an increase in density causes an increase in oxidation and thereby reduces the thermal stability of the biodiesel. The cloud point is also a critical parameter for low-temperature applications of fuel. Biodiesel is known to have a higher cloud point than conventional diesel, which makes it more suitable to use in the hot climatic conditions of KSA. However, the cloud point of biodiesel decreases by blending with petrodiesel, as both are completely miscible with each other (Rajagopal et al., 2012).

The oxidative stability of biodiesel is also affected by the cold flow properties of the biodiesel such as cloud point, pour point and cold filter plugging point (CFPP). Zuleta et al. (2012) have reported that palm biodiesel, having the highest amount of saturated methyl esters, has high CFPP value of 14 ^{o}C due to its reactivity towards oxidation due to allylic moieties in their chains. The cloud point is mainly affected by the fatty acid composition of biodiesel (Rajagopal et al., 2012). Biodiesel blends are observed to have different cloud points than the net biodiesel. The cloud point changes with the chain length of saturated and unsaturated FAME, which mainly depends on the degree of unsaturation and orientation of the double bonds (Zuleta et al., 2012).

There are theoretical and statistical studies carried out on the biodiesel production with different feedstocks and methods to ascertain cold flow properties (Chen et al., 2012). These studies have indicated that an optimised FAME composition can be obtained and used to gain an improvement in low-temperature properties of biodiesel. The pour points of various oils usually range from -15 to +22 ^{o}C. The use of additives has been reported to suppress the crystal growth stages during the wax crystallization process, thereby reducing the pour point (Zuleta et al., 2012).

4.5 Future perspectives

The biodiesel industry is an emerging alternative for managing the demands of transportation, industrial processes, and residential consumption by being eco-friendly, biodegradable and readily available feedstocks. Although the biodiesel industry is still facing many challenges, the research since last 20 years offers the possibility of utilizing a wide range of feedstocks, cost reductions, and process optimisations. The higher cost of production while using vegetable oils has led to exploring new plant and animal-based feedstocks and non-edible resources. Various catalysts and their modifications are still being widely researched. For instance, an immobilized lipase catalyst whose reusability after five times reduced the overall manufacturing cost to about US 2000 $ per ton, which is 206% higher than alkali process but less than the conventional enzyme process by 324% (Jegannathan et al., 2011). This has led to the development that if the reuse capability of a catalyst is increased, it can compete with the alkali catalyst process and as a consequent, the biodiesel production cost can be reduced significantly.

Moreover, in different methods solvents such as supercritical methyl acetate without catalysts are being used to increase the yield and quality of biodiesel (Saka and Isayama, 2009). In the near future, apart from feedstock choice, the catalyst selection, biodiesel production method, parameters affecting the process and the production cost, and blending and use of additives for improving the quality of biodiesel are the critical topics of investigation. These factors will determine the production cost of biodiesel along with improving its efficiency and the possibility of commercializing the biodiesel products on a larger scale. The choice of additive depends on its influence on the combustion performance and emissions from a diesel engine, oxidation stability, and the fuel quality according to the ASTM and EN standards (EN, 2003). Despite the use of different strategies to improve the quality and yield of biodiesel, there are still things to be done in the areas of improving the cold flow properties, oxidation stability and viscosity of biodiesel through pre-blending of different feedstocks and post-blending of biodiesels from various sources in order to make biodiesel fuel more efficient and economically feasible.

The sustainability of the biodiesel if produced from waste feedstocks has to be assessed against energy and GHG balances along with its environmental and social acceptability. In this regards, the life cycle assessment (LCA), cradle to grave approach, is a valuable tool to understand the environmental and economic benefits of the process and its products (Nizami et al., 2017). LCA mainly consist of steps such as functional unit, scope, system boundary, reference system, data source and allocation (Rathore et al., 2016). The proposed waste to biodiesel technologies would be multi-dimensional, since various waste feedstocks for biodiesel production as well as other value-added products involved. It is, therefore, crucial to conduct detailed LCA studies to understand these processes better. The authors are also working on detailed LCA studies to highlight the challenges and detailed economic and environmental benefits to help the KSA government and other stakeholders to decide on developing waste to biodiesel production technologies in KSA. These studies would be equally useful for other countries, in particular for developing countries to move towards circular economies.

5. Conclusions

KSA holds tremendous potential to develop waste to biodiesel facilities utilizing various types of wastes which otherwise end up in landfills. The diversion of waste from landfills would help the country to shift from oil-based economy towards a circular economy. The fat fraction of MSW in KSA has been examined to underpin the economic and environmental benefits, which would multiply many folds if applied to other available wastes such as slaughterhouse waste, WCO, agricultural waste, sewage sludge, inedible oils, and microalgae. However, there are limitations of feedstock collection, fat fraction separation and regulatory framework in commercializing these facilities.

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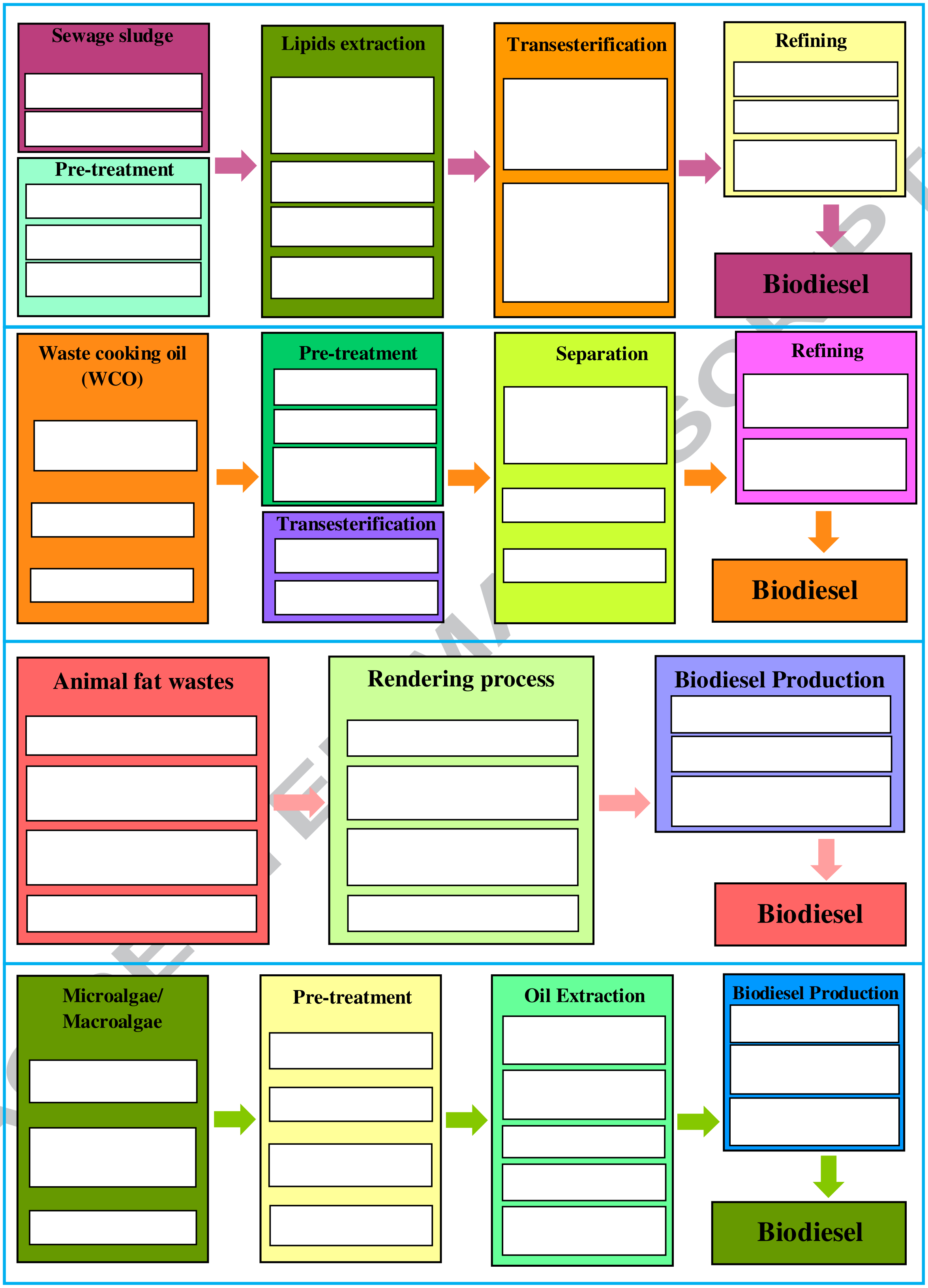

Figure 1. Biodiesel production from various sources (Kargbo, 2010; Shahzad et al., 2017)

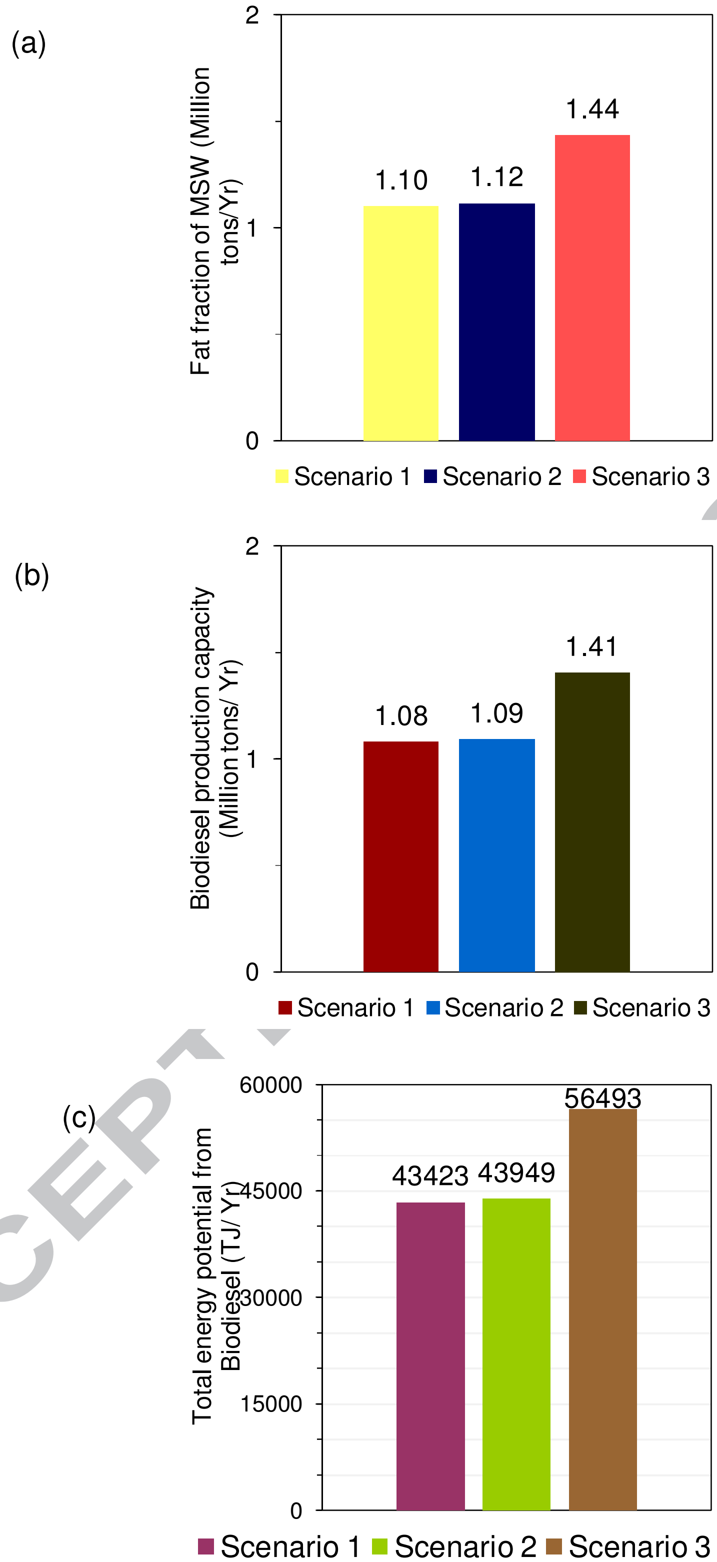

Figure 2. The estimated values for all three scenarios; a) fat fractions of MSW, b) biodiesel production capacity, c) total energy potential from biodiesel.

Table 1. A comparison of properties of petrodiesel with biodiesel produced from various waste sources/feedstocks (Hajjari et al., 2017)

Characteristics	Units	Petrodiesel	Waste fish oil	Waste poultry fat	Waste cooking oil (WCO)	Tallow from beef and mutton
Viscosity at 40 °C	mm^2/s	3	5	4.5	4.7	6.4
Cetane number	-	51 (Euro 3, 4, 5)	51	61	50	59
Sulphur contents	ppm	350 (Euro 3) 50 (Euro 4) 10 (Euro 5)	-	-	range	0.2
Density at 40°C	kg/m3	0.82	0.86	0.87	0.87	0.86
Heating value: high heating value (HHV) and low heating value (LHV)	MJ/kg	LHV=43 HHV=47	41.5	61	40	40
Acid value	mg KOH/g	-	1.2	0.3	2	0.6
Cloud point	(°C)	-5	-5	-6	20	-4
Flash point	(°C)	50	-	-	86	-
Pour point	(°C)	-	4	-6	16	-5
Short chain unsaturated fatty acids (C:14-C:18)	%	-	30-60	65-80	40-80	35-65
Short chain saturated fatty acids (C:14-C:18)	%	-	15-30	20-35	20-45	40-60
Long chain unsaturated fatty acids (≥C:20)	%	-	25-40	0-(-2)	0-1	0-0.5
Long chain saturated fatty acids (≥C:20)	%	-	0-7	0-2	0-1	0-1

Graphical abstract