Recycling and Reusing Aspect of Green Circular Economy to Overcome Engineering and Environmental Challenges

Abstract

The environmental issues of mineral oil-based drilling muds and additives in spite of their excellent technical performance such as good lubricity and high wear protection characteristics and the technical issues of water-based drilling muds such as the poor lubricity and wear resistance characteristics in spite of their excellent environmental traits require the development of high performance water-based drilling muds to overcome the current as well as the future drilling engineering and other oil and gas field challenges. Hence, several value-added green products have been developed adopting the recycling and reusing aspect of green circular economy of waste cook oil (WCO) to develop eco-friendly fluid additives and demonstrate their applications to explore and exploit oil and gas resources without any damage to the terrestrial, coastal and the marine environments and the ecosystems.

Analyses of technical performance of the WCO derived green products with respect to the equivalent commercial products indicate similar or superior technical performance with the added benefit of no environmental impact. Hence, the recycling and reusing of the WCO provide a sustainable circular economical route for ecofriendly product development to overcome the technical and the environmental challenges simultaneously. It also provides a potential avenue for the growth and development of local, regional, national and global industries and infrastructures, development and creation of new job opportunities for the local, regional and the global communities, especially in developing and under-developed countries to create a positive societal and economic impact. Although this paper highlights mainly the oil and gas industry applications, WCO has huge potential for other industrial applications to overcome the technical problems without any negative environmental consequences. It can be used as a sustainable raw material for the development of a large variety of value-added green chemicals and polymers such as plasticizers, binders, surfactants, eco-greases, biopolymers, etc for other industrial applications. The renewable, sustainable and locally available source of the raw material have high potential to bring long-term stability to the oil and gas field additive supply chain for continuous and uninterrupted drilling and production operation. The paper highlights the applications of several WCO-based value-added products to overcome the technical and environmental challenges faced by the oil and gas industry.

Introduction

Huge amount of food wastes is generated each year locally, regionally, nationally and globally. Figure 1 shows several categories of common food wastes generated each year based on information published in the National Geography.com (2016). It clearly shows a significant amount of the food is wasted each year in spite of huge food shortages for the global communities. Strategic policies on waste minimization and waste management can turn the huge amount of bio-based food wastes into valuable resources to improve global food security and ensure a sustainable source of raw materials to develop products and additives for various industrial applications. For example, elimination or minimization of these food wastes could feed millions of hungry people and thus could have a positive impact on global food security. According to National Geography.com (2016) about 2.9 trillion pounds of food is wasted each year and more than 800 million people remain hungry due to no or insufficient food to meet their daily need. Althumiri et al. (2021) highlighted the importance and co-existence of food waste and food insecurity in developing and developed countries along with their relationships at the household and individual levels. As per FAO (2011) statistics, nearly 1/3 of the total food produced by the world is wasted in each year which is equal to 1.3 billion tons/year. Kaza et al. (2018) highlighted the production of 2.01 billion tons of municipal solid wastes each year globally and about 44% of these waste products are the food and green wastes. Hence, the eradication or minimization of the negative impact of food wastes by optimum consumption, promoting the recycling and reusing aspect of circular economy along with no/negligible food waste generation is one of the major steps for a sustainable food security and preservation of ecofriendly global environment for the mankind. That's why United Nations (2018) report on sustainable consumption and minimum production of food waste highlighted the reduction of food waste as one of the global Sustainable Development Goals (SDGs) to enhance the global food security.

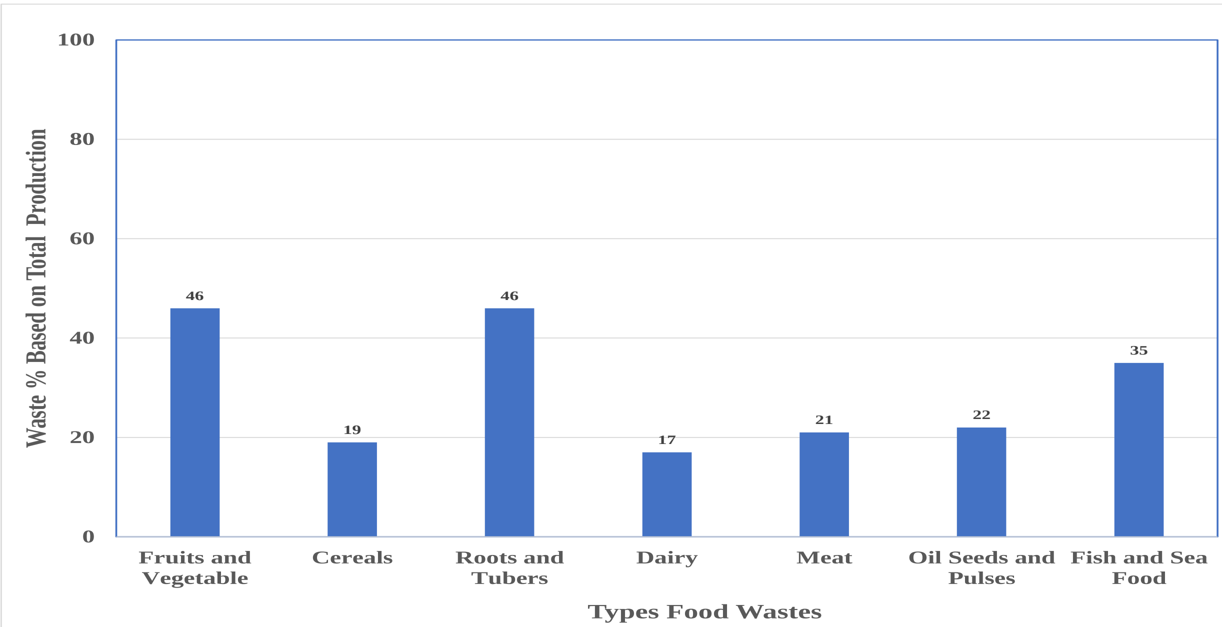

Figure 1 Various Types of Food Wastes Generated based on Total Yearly Production (Data Source: National Geography.com, 2016)

Reduction of food loss and food waste is not only important to fulfill the UN's Sustainable Development Goals but also to protect the global environment. It is very critical to mitigate the negative economic, social and environmental impacts associated with the illegal disposal of the huge volume of waste food into the surrounding environments and the ecosystems. According to Caldeira et al. (2017) the current estimates of average food wastes generated in Europe ranges from 173 and 290 kg/person/yr. The authors further highlighted that nearly 60% of the food waste is the residues arising after consumption and post consumption of the edible foods. According to the Economist (2017) the per capita food waste in Australia is about 361 kg/person/yr, in USA 278 kg/person/yr, in Canada 123kg/person/yr, in India 51kg/person/yr, in China 44kg/person/yr. Most of these food wastes are discarded in landfills or sent to incinerators and thus create a multitude of environmental and public health problems.

However, the culture is changing due to the enactment of increasingly strict environmental laws and regulations by the EPAs, local, state and federal governments of various countries and also due to the increasing awareness of the public and the global communities. This is reflected by the promotion and adoption of different circular economy and circular development approaches such as recycling, reusing, repairing, modification, refabrication, etc for valorization of food wastes and other waste products by developing a variety of new and upgraded products along with chemicals, materials, biofuels, green additives, etc for various industrial applications (Amanullah et al. 2019, Dahia et al. 2018, Lin et al., 2013, Salimi et al. 2020). The selection of circular economy approaches and the valorization processes depend on the nature and the composition of the abiotic and the bio-based wastes. However, all of them can be brought under the umbrella of circular economy to turn wastes into valuable assets, develop new or modified products and create an ecofriendly, healthy and prosperous future for the global communities.

Various amount of bio-based food wastes is generated by different industrial sectors all over the world. A large fraction of the global food waste arises after the edible life cycle of fats and oils used by the food and catering industries, households, restaurants and other food processing centers. Therefore, each and every country of the globe generate a huge amount of non-edible waste cooking oil each year. According to Avinash and Murugesan (2018) more than 20% of the cooking oils is generated as waste oil in households, restaurants, food processing centers, etc. Gui et al. (2008) and Lin et al. (2013) have highlighted the production of more than 15 million tons of waste vegetable oils annually in the world with European Union (EU) close to 1 million tons/year. According to EPA (2011) statistical report the collectable waste cooking oil from food restaurant is about 3 billion gallons/year. Even though there is some variation in the quantitative values highlighted by various authors, reports and sources, all of them indicate the generation of a huge quantity of waste cooking oil each year.

Waste cooking oils generated after the end of their edible life cycle are not fit for human consumption due to its degradation as a result of various chemical reactions such as hydrolysis, oxidation, chemical degradation, thermal decomposition and polymerization of the oil (Tsai 2019, Sodhi et al. 2017) along with the augmentation of polar materials and the reduction of the unsaturated fatty acids during cooking process. However, due to organic nature, renewable source and sustainable supply of WCO, it is a highly viable alternative to finite source and non-ecofriendly petroleum oils for developing different green products and additives for various industrial applications including the vibrant oil and gas industry of the world to explore and exploit oil and gas resources without any negative impact on the terrestrial, coastal and the marine environments and the ecosystems along with other non-hydrocarbon-based resources.

Unfortunately, most of the WCOs are currently disposed illegally to the surrounding environments and ecosystems. According to Chhetri et al. (2008) even though some of these WCOs is used for soap production, a major part of the WCOs is discharged into the environment illegally by households and restaurants, food frying and food processing facilities, catering industries, etc after the end of their edible life cycle. In spite of their ecofriendly, biodegradable and virtually non-toxic nature, disposal of huge amount of WCOs in the sinks, drainage systems, canals, rivers, water ways, ecosystems, landfills, etc can cause numerous ecological, environmental and municipal problems due to the oxygen and light depletion effect on aquatic lives, blockage of drainage and waterways and the eutrophication effect of excessive minerals and nutrients on the disposal or accumulated sites. Eutrophication is the result of high nutrient-induced increase in phytoplankton, micro-organisms and algal growth in waterways, landfills, drainage systems, marshes, canals, lakes, water reserves, etc. It highlights the need of development of suitable recycling facilities to eradicate the scope of illegal disposal. Moreover, the recycling and reusing of the huge amount of WCOs will facilitate the development and synthesis of various green products and additives to meet the ecofriendly product demands of various industries including the vibrant oil and gas industry of the world.

The negative societal and environmental impact of the huge amount of waste cooking oils generated each year can be eradicated or minimized by several ways. Firstly, the reduction of the use of edible cooking oil and the mitigation of the generation of the amount of waste cooking oils as much as possible to fulfill the UN’s Sustainable Development Goals highlighted in United Nations (2011) report on judicial and optimum consumption and minimum wastes generation to enhance the global food security. Secondly, by recycling and reusing to turn the useless wastes into valuable assets to develop various green products and chemicals for different industrial applications. The recycling and reusing approach of circular economy and circular product development process of valorization of the WCO will play a leading role to mitigate their negative societal and environmental impacts. Recent publications highlighted the applications of various circular economy approaches for valorization of food wastes for different industrial applications (Dahiya et al. 2018, Lin et al. 2013, Salimi et al. 2020). This paper highlights the recycling and reusing aspect of circular economy of WCOs to develop several value-added green additives for oil and gas field applications.

Recycling, Reusing and Circular Economy

Circular economy and circular development process were well known to the ancient nations and civilizations. Off course, the ancient nations and civilizations never highlighted the repeated use of virgin and waste materials for various applications to maximize resource efficiency and minimize cost as circular economy. They used household ashes arising after burning the wood and other solid fuels for cooking foods as a cleaning agent for their dishes, beauty care product to shampoo their hairs, insect control agent in the garden, soil fertilizer to improve the crop productivity, soil hardener to build a long-lasting soil wall, etc. Use of plants and wood for furniture, bridges, building materials, wood savings and wastes as solid fuel, sealing and blocking water leaks, burnt rice husk and wood ash as tooth pastes, etc also highlights the ancient root of the circular economy. The current push for the application and adoption of the circular economy against the conventional linear economy model is just a renewed effort of the modern communities for the old circular economy to benefit the mankind.

Various authors, foundations, forums, and websites have defined the current concept of circular economy in a variety of ways. However, the fundamental philosophy of the current circular economy concept is very similar to the unpublished ancient concept. Some of the current definitions of circular economy are highlighted below.

Ellen MacArthur Foundation (EMF) has defined circular economy as a new industrial model that is looking beyond the current take-make-dispose-based linear industrial model to redefine growth focusing on positive society-wide benefits. It promotes gradual decoupling of traditional economic activity from the consumption of finite resources to renewable resources to ensure sustainable sources of supply of products, services and chemicals and designing waste out of the system to maximize resource efficiency, minimize wastes generation and eliminate or reduce the environmental footprint. It is based on three principles: design out waste and pollution; keep products and materials in use; regenerate natural systems (EMF 2013). According to UNIDO (2017) circular economy is a new way of creating value and ultimate prosperity by extending product lifespan, maximizing resource efficiency, minimizing waste generation, reducing resource dependency, recycling and reusing industrial and natural waste resources to reduce environmental footprint and creating an extra avenue for revenue generation.

According to the concept of circular economy defined by McCarthy et al. (2018) and adopted by OECD, it is the industrial process of increased product repairing and remanufacturing for development of robust long-lived products through design, recycling and re-using to maximize resource efficiency and material productivity, improve asset utilization and modify consumer behavior. The positive impact of these features of circular economy is the decreased demand for new goods, substitution of primary raw materials by secondary raw materials, expansion of secondary sector and development of more durable and repairable products along with the expanded sharing culture and service economies. World Economic Forum (WEF) defined circular economy as an industrial system that is restorative and regenerative by intention and design. It differs from the conventional linear economy model due to the replacement of the traditional 'end-of-life' concept with restoration along with the shifting from the use of non-renewable and unsustainable energy to renewable and sustainable energy, elimination of the use of toxic products and chemicals that create a barrier for recycling and reusing along with the eradication or minimization of wastes through superior design of materials, products, systems, processes in the context of circular economy (WEF, 2020). According to the European Parliament News (2021) circular economy is a new model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling of existing materials and products as long as possible to extend the life cycle of the products as much as possible.

In spite of some variations in the circular economy concept and definitions described above, all of them highlighted the Recycling and Reusing of one industry wastes to create value added products for the same or other industrial applications as an inseparable part of circular economy and circular product development process. Like the ancient and the current circular economy concept, the recycling and the reusing of the WCO aimed to reutilize the waste cooking oil to minimize the ultimate waste production and maximize the resource efficiency to protect the finite source natural resources and turn useless waste products and by-products into valuable assets to create a positive technical, economic, social and environmental impact. However, due to the lack of some of the elements of a true circular economy model, the authors consider the recycling and reusing of the WCO oil as a pseudo-circular economy.

Some of the major advantages and benefits of the circular economy and circular product development aspects of recycling and reusing of various industrial wastes including the WCO generated by the food and catering industry are summarized below.

- It turns liability to a valuable asset for extra revenue generation.
- Reduces wastes sent to landfills and incinerators.
- Eradicates or reduces greenhouse gas emission
- Promotes circular economy and circular development process to preserve natural resources and maximize resource efficiency.
- Prevent pollution and contamination to conserve and protect the global environments and the ecosystems
- Provide a potential avenue for localization of product development to increase local content and reduce import from overseas countries
- Create a positive societal impact due to new job creation and contributing in community development
- Provides simultaneous solutions of several industry problems to maximize the economic benefits
- Act as a powerful catalyst for the growth of existing industries and development of new industries, infrastructures and biorefineries.

WCOs Recycling

Several liters of waste cooking oils were collected from a local restaurant to demonstrate the potential of recycling of the WCO to develop several ecofriendly products for oil and gas industry applications. The recycling process consisted of physical pretreatment followed by transesterification of the waste cooking oil. Physical treatment was done using a low pressure filtration cell and a 5-micron hardened filter paper at room temperature under 10-12 psi pressure to separate all food debris, burnt spices and other colloidal particles from the waste oil to improve the processability in the transesterification process. Then transesterification was done using methanol and NaOH as the catalyst to knock down the viscous properties of the waste oil to a level that is comparable to the viscous characteristics of mineral oils. Figure 2 shows a pictorial view of the transesterification process and Figure 3 shows the transesterification reaction that took place to produce the waste vegetable oil ester (WCO Ester). Reusing potentials of the WCO ester was demonstrated by developing an ecofriendly base stock for formulation of a green lubricant, an Eco-OBM system and also an eco-friendly spotting fluid. These products were tested and evaluated using test methods and standards used by the oil and gas industry.

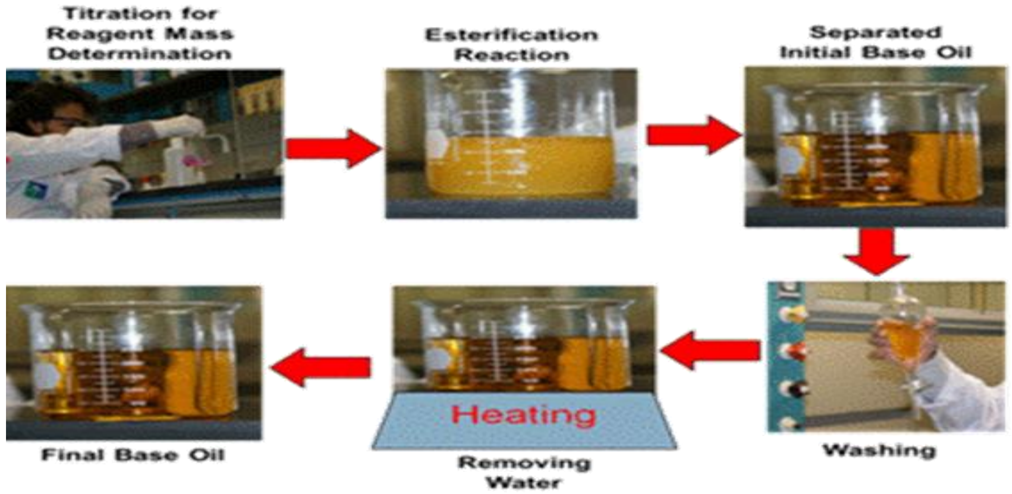

Figure 2 Pictorial Diagram Showing the Recycling Process of Waste Cooking Oil (WCO)

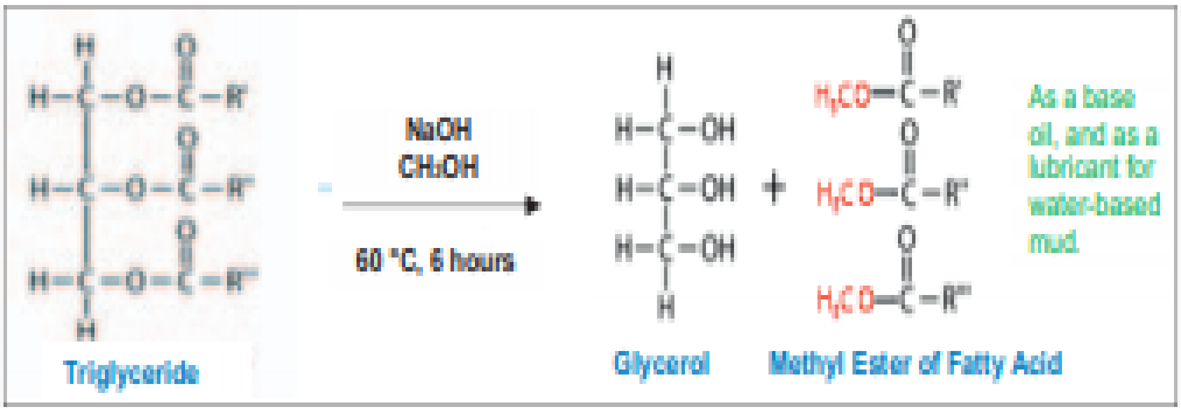

Figure 3 Shows the Esterification Reaction of WCO and Methanol in the Presence of NaOH Catalyst

Reusing as an Ecofriendly Base Fluid

The newly developed WCO Ester will qualify as a base fluid for an Eco-OBM formulation if it can generate rheological profile and the PV (plastic viscosity) within the desirable range of mineral oil or highly refined mineral oil used by the industry. Figure 4 clearly indicates that the esterification process provided an eco-friendly base stock with viscous characteristics similar to mineral and the highly refined Safra oil (SAO) widely used as the base stocks for conventional OBM development. The original WCO has significantly high viscous characteristics than the mineral and Safra oil (see Figure 4). That's why the "as received" WCO cannot be used to formulate Eco-OBM systems. The recycled WCO i.e., WCO ester produced after chemical modification has rheological profiles in the proximity of mineral oil and thus demonstrates its potential to use as a base stock for ecofriendly OBM formulations. Acceptable rheological properties of the base fluid used for OBM formulations is very important for a viable mud formulation for safe, economic and hazard-free drilling operation.

Plastic viscosity (PV) of the base fluid provides another indication about the suitability of a base oil in formulating an oil-based mud with desirable rheological properties. A PV value of the base fluid should be as low as possible, ideally below 10 to formulate a mud system with acceptable PV range. Figure 5 clearly shows very high PV for the original waste cooking oil and thus indicates its non-suitability for OBM formulation. Comparison of plastic viscosity (PV) of recycled WCO i.e., the WCO ester with the PV value of the mineral oil indicates very close proximity and thus the suitability of the WCO ester for Eco-OBM formulations.

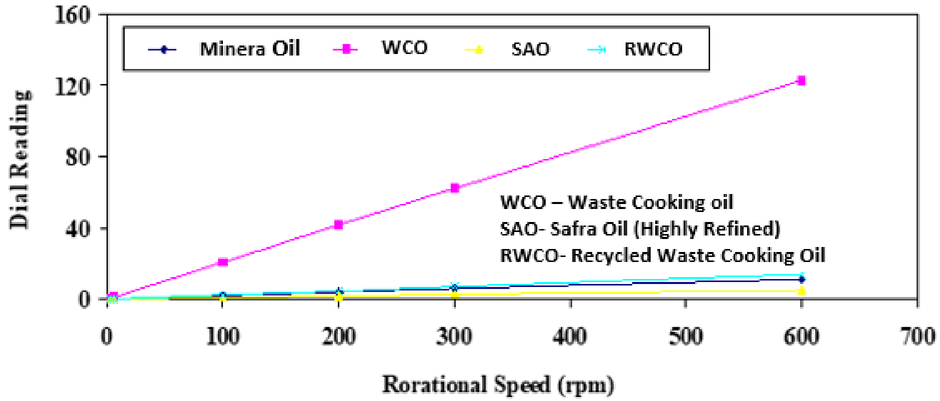

Figure 4 Viscous Profiles of Mineral Oil, Waste Cooking Oil (WCO), SAO (Safra Oil) and Recycled WCO (WCO Ester)

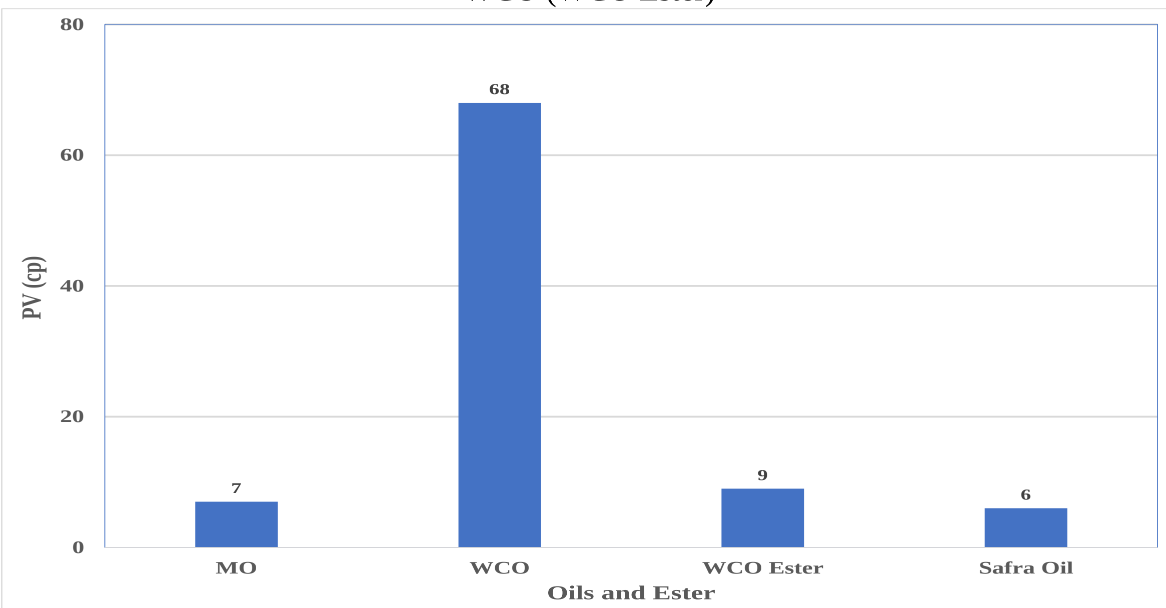

Figure 5 PV of Mineral Oil (MO), Waste Cooking Oil (WCO), WCO Ester and Safra Oil

Reusing as a Lubricant for WBMs

Various types of water-based muds starting from simple clay-based mud at the surface hole sections to mono and divalent water-based muds, silicate mud, polymer mud, etc at deeper hole sections are frequently used to explore and exploit oil and gas resources to meet the global energy demand. All of these water-based mud systems have high COF values (see Figure 6) compared to oil-based muds without the presence of a lubricant (Amanullah et al 2019, Mondshine 1970, Growcock et al., 1999). According to Redburn et al. (2013) COFs of water-based drilling fluids generally range from 0.15 to 0.45, but typically vary from 0.20 to 0.28 and the COFs of Oil based muds generally range from 0.05 to 0.15, but typically vary from 0.07 to 0.14. Figure 6 shows some published values of several water and an oil-based muds. The data clearly show much higher COF values for water-based muds compared to the oil-based mud. That’s why one or more lubricants are added to water-based muds to reduce the COFs to a level that is close to an oil-based mud.

Most of the traditional lubricants are mineral oil-based and thus not ecofriendly in nature. Incorporation of these lubricants into water-based muds may turn the ecofriendly water-based mud into non ecofriendly drilling mud system. Hence, the petroleum oil-based products and additives including the mineral oil-based lubricants are facing increasingly tough restrictions due to the enactment of progressively strict environmental laws and regulations by EPAs, local, state and federal governments of various countries. This problem can be solved by incorporating a green lubricant into the water-based mud to fulfill the functional tasks without compromising the environmental standing of the water-based mud.

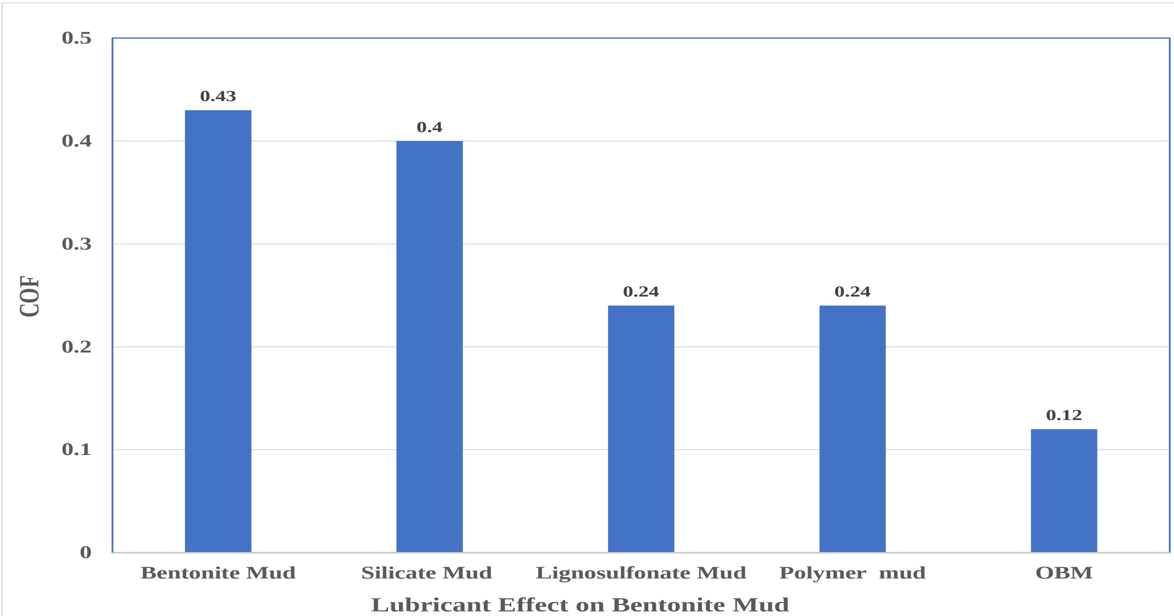

Figure 6 Typical COF Values of Water and Oil-based Drilling Muds

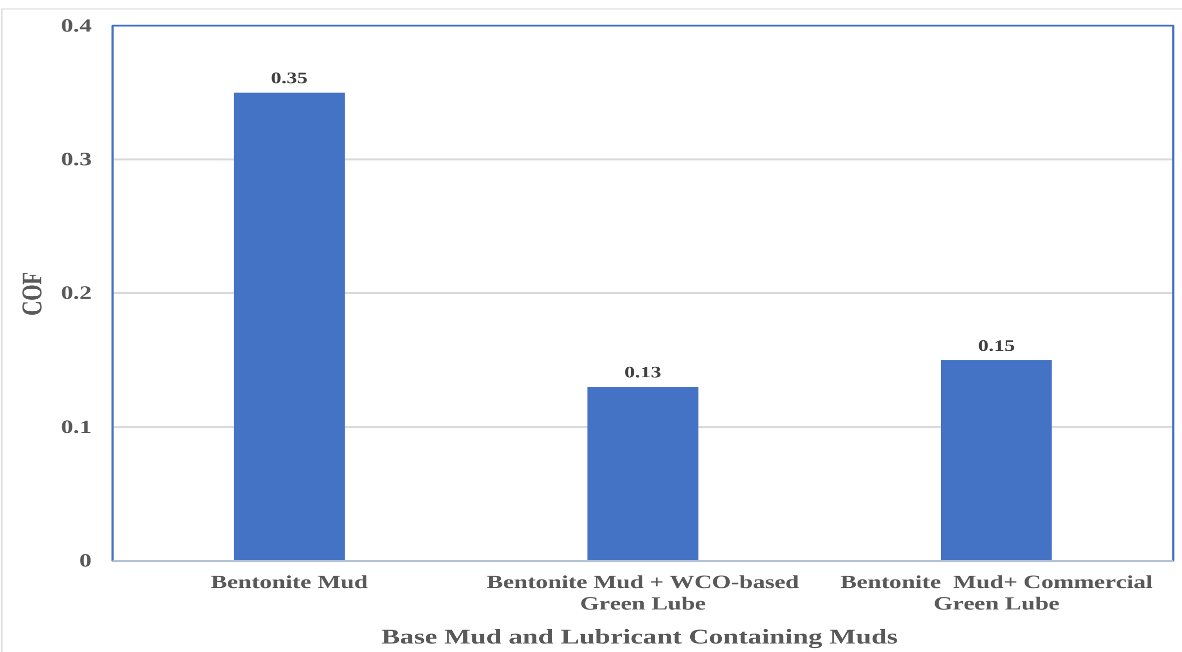

Figure 7 COF Values of Bentonite Mud and Green Lubricant Containing Bentonite Muds

Reusing of the waste cooking oil ester developed after recycling the WCO as an ecofriendly lubricant was evaluated using standard lubricity tester and test method used by the oil and gas industry. Two water-based muds such as a bentonite mud and a LSND mud system were used to evaluate the effectiveness of the WCO ester as an ecofriendly lubricant. A detail description of the lubricity tester and the test method can be found in Amanullah (2016). The experimental results are given in Figures 7 and 8. Figure 7 shows the lubricating efficiency of the WCO Ester-based green lube on clay-based mud system and Figure 8 shows the lubricating potential in LSND (Low Solids Non-Dispersed) mud system.

Figure 7 clearly indicates that the WCO derived green lubricant has good friction reducing properties in clay-based bentonite mud. That's why it was able to knock down the coefficient of friction (COF) of the bentonite mud by more than 60% compared to the COF value of the base bentonite mud containing no lubricant. Comparison of the performance of the newly developed green lubricant with a commercial green lubricant shows better performance for the WCO ester-based lubricant in the clay-based bentonite mud with respect to the high-cost commercial green lubricant. Hence, the WCO provides a cheaper avenue for ecofriendly lubricant development to enhance water-based mud lubricity and protect the global environment and the ecosystems. Figure 8 shows considerable reduction of the COF value of the LSND mud due to the incorporation of WCO ester-based green lubricant into the mud system. It indicates about 30% reduction of the COF values of the LSND mud compared to the LSND mud containing no lubricant. Comparison of the performance of the newly developed green lubricant with a commercial green lubricant shows somewhat lower performance for the WCO ester-based lubricant in LSND mud compared to the commercial green lubricant.

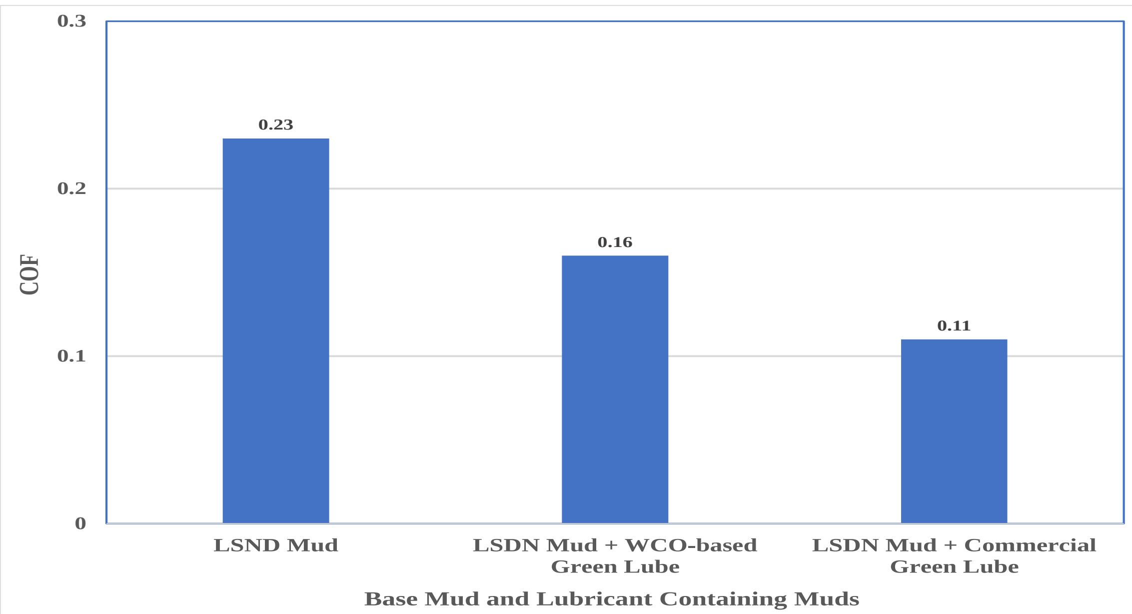

Figure 8 COF Values of LSND Mud and Green Lubricant Containing LSND Muds

Reusing for an Eco-OBM Development

Due to the poor performance of water-based muds in reactive shales, marls and mudrocks and also in HTHP and extreme drilling environments, oil-based drilling muds are extensively used due to their insensitivity to reactive shales and mudrocks, higher capability to withstand high temperatures and acid gases, faster rate of penetration and high lubricating potential in deviated, horizontal and extended reach wells, capability to reduce the scope of differential sticking and mud contamination effect by various mud contaminants, etc. Typically, diesel and mineral oil-based muds are used in many parts of the world which are not ecofriendly, poorly biodegradable and virtually toxic. Hence, there is a push to develop an ecofriendly alternative to currently used diesel and mineral oil-based muds. The importance of using environmentally acceptable oil-based muds were highlighted by various authors (Amanullah, 2005 Ezzat and Al-Buraik, 1997, Dosunmu and Ogunrinde, 2010, Sanchez et al., 1999) to safeguard the global environments and the ecosystems.

Due to high biodegradability, ecofriendly nature and virtually non-toxic characteristics of WCO (Amanullah 2016, Dosunmu and Ogunride 2010), it was used to develop an environment friendly Eco-OBM system. An Eco-OBM system will allow the exploration and exploitation of oil and gas resources without causing any damage and degradation to the terrestrial, coastal and the marine environments and the ecosystems and also other valuable resources. Yassin et al. (1991) highlighted the importance of an eco-friendly oil-based mud as an attractive alternative to safeguard the global environment.

Table 1 shows the formulation of a 75/25 Eco-OBM system along with the formulation of a 75/25 Safra oil-based mud. The widely used Safra oil-based mud was included for comparative assessment of the performance of the recycled waste cooking oil-based Eco-OBM system. The muds were prepared using a high-speed homogenizer by mixing the components in the order shown in Table 1. However, $CaCl_2$ was mixed in the water phase before adding and mixing to the rest of the OBM system.

Table 1 Formulations of a 75/25 Safra Oil-based Mud and a 75/25 Eco-OBM Systems

75/25 Safra OBM		75/25 Eco-OBM	
Mud Components	**Value**	**Mud Components**	**Value**
Safra Oil	200	WVO Estrer	200
Primary Emulsifier (cc)	13	Primary Emulsifier (cc)	13
Lime (gm)	3	Lime (gm)	3
Duratone (gm)	6	Duratone (gm)	6
Water (cc)	67	Water (cc)	67
Geltone (gm)	2	Geltone (gm)	2
Secondary Emulsifier (cc)	2.1	Secondary Emulsifier (cc)	2.1
$CaCl_2$ (78% purity)	61	$CaCl_2$ (78% purity)	61
Barite (gm)	0	Barite (gm)	0

Testing and Evaluation

Traditional laboratory testing tools and equipment used by the oil and gas industry were used to measure the rheological properties, gel strength and electrical stability of oil-based muds to evaluate the viscous properties, gelling characteristics and the electrical stability (ES) of WCO Ester-based Eco-OBM system and the conventional safra oil-based drilling mud. Figures 9-12 shows the experimental results in graphical forms.

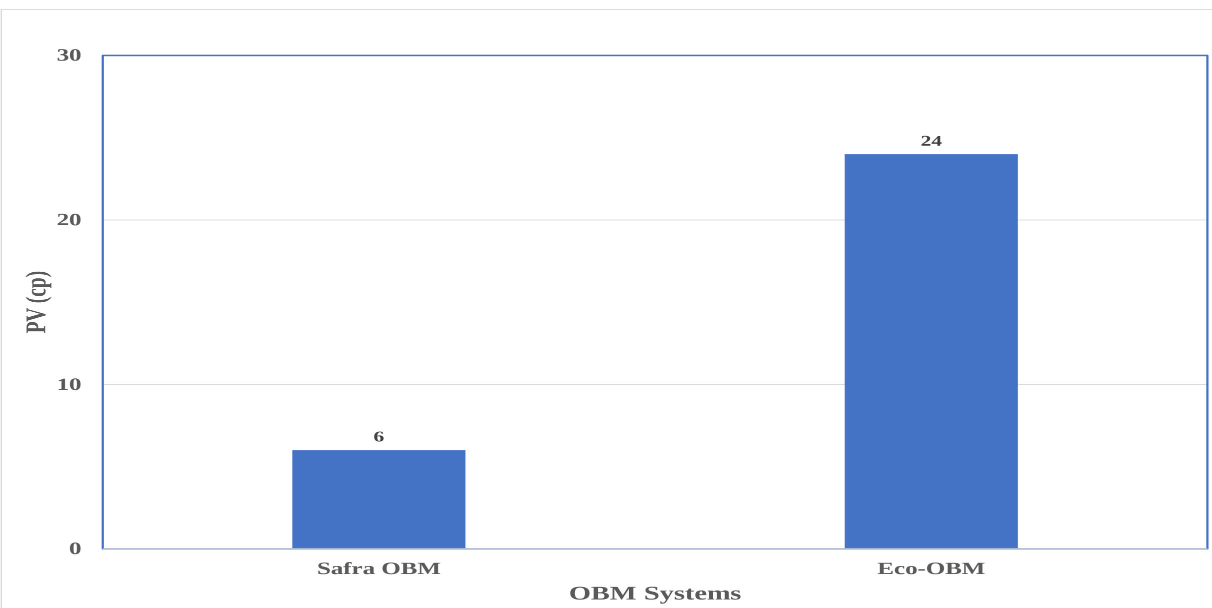

Figure 9 PV Values of Safra Oil and the WCO-based Eco-OBM System

Figure 9 shows the PV calculated based on the 600 and 300 rpm readings of the viscometer for safra oil and WCO ester-based Eco-OBM system. The Eco-OBM shows higher PV values compared to the Safra oil-based mud at the same viscosifier loading (see Table 1). Drilling operation prefers PV as low as possible. However, a PV below 30 is acceptable for unweighted mud systems. The Eco-OBM shows a

PV less than the maximum acceptable value (see Figure 9). However, if required, the PV of the WCO ester-based Eco-OBM system can be reduced further by decreasing the amount of viscosifier (geltone) used in the formulation of the Eco-OBM system. Lowering of the amount of geltone (viscosifier) will also reduce the formulation cost of the Eco-OBM system.

YP of drilling mud is an indicator of the cuttings carrying capacity and the hole cleaning efficiency of the drilling mud while circulating the mud from the surface to the bottom and then back to the surface along with the generated drill cuttings. An YP value in the range of 15-30 is acceptable for adequate hole cleaning to avoid any problems associated with poor hole cleaning. Drilling muds having YP value lower than the minimum acceptable value will cause settling and sagging problems leading to poor hole cleaning and cuttings bed formation along with other drilling problems. Okranzi and Azar (1986) and Becker et al. (1991) highlighted the requirement of an YP value in the range of 15 – 25 lbs/100 ft^2 for optimum hole cleaning and cuttings transportation from the bottom of the hole to the surface.

Figure 10 shows superior YP value for the WCO ester-based Eco-OBM system compared to the safra oil-based mud at the same amount of viscosifier loading. The safra oil-based mud shows YP value well below the minimum acceptable range at this concentration of viscosifier (geltone). It indicates that the safra oil-based mud will require much higher amount of viscosifier to generate desirable YP values. The WCO ester-based Eco-OBM indicates an YP value equal to 18 that is within the desirable range. The result clearly indicates that a lower amount of viscosifier can generate sufficient YP value for the Eco-OBM system to full the functional tasks and avoid the hole cleaning and other drilling problems.

Figure 10 also shows the low shear yield point (LSYP) of the safra oil and the Eco-OBM systems. An LSYP value within the range 7-14 lbs/100 ft^2 is desirable to avoid hole cleaning, cuttings and weighting materials settling problems along with other drilling problems. Bern et al (1996) highlighted an LSYP value in the range of 5-15 lbs/100 ft2 for preventing sagging and improving the hole cleaning efficiency at low shear condition. The Eco-OBM system shows a LSYP value equal to 9. However, the safra oil-based mud shows a very low LSYP value equal to 1 at the same concentration of the viscosifier. Hence, the safra oil-based mud will create severe hole cleaning and other drilling problems at low shear condition at the upper section of the wellbore. It again indicates the requirement of much higher viscosifier for the safra oil-based mud compared to the WCO ester-based Eco-OBM system. Generation of desirable YP and LSYP values using low concentration of geltone in the WCO ester-based Eco-OBM system demonstrates the potential of reusing the WCO to develop an ecofriendly alternative of conventional oil-based muds.

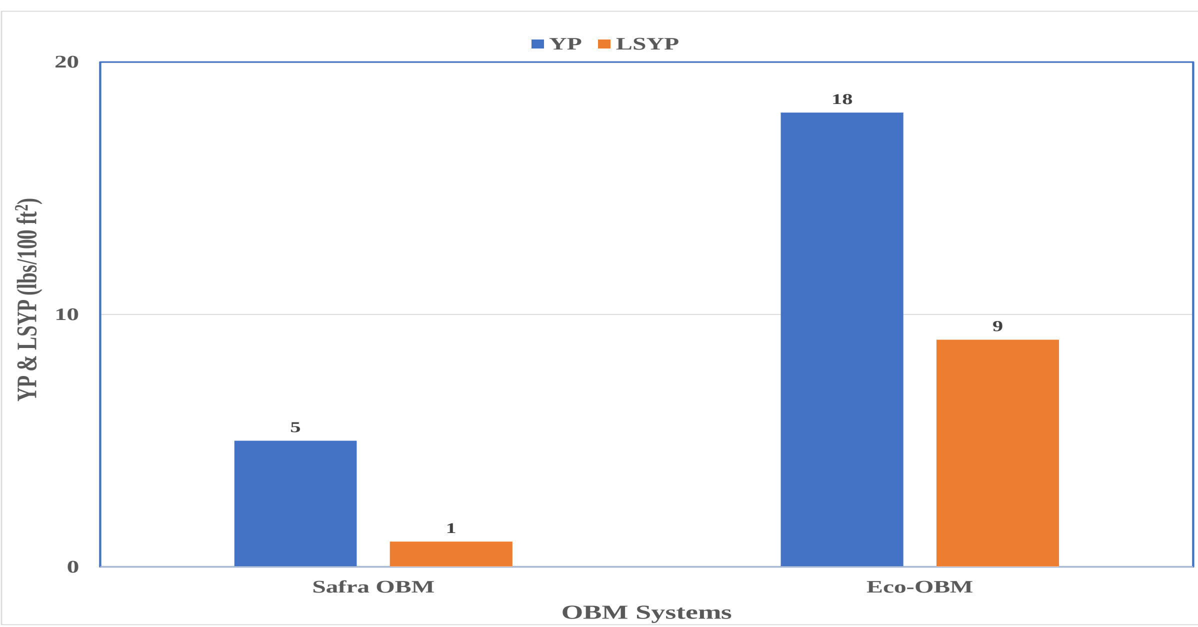

Figure 10 YP and LSYP Values of Safra Oil and the WCO-based Eco-OBM System

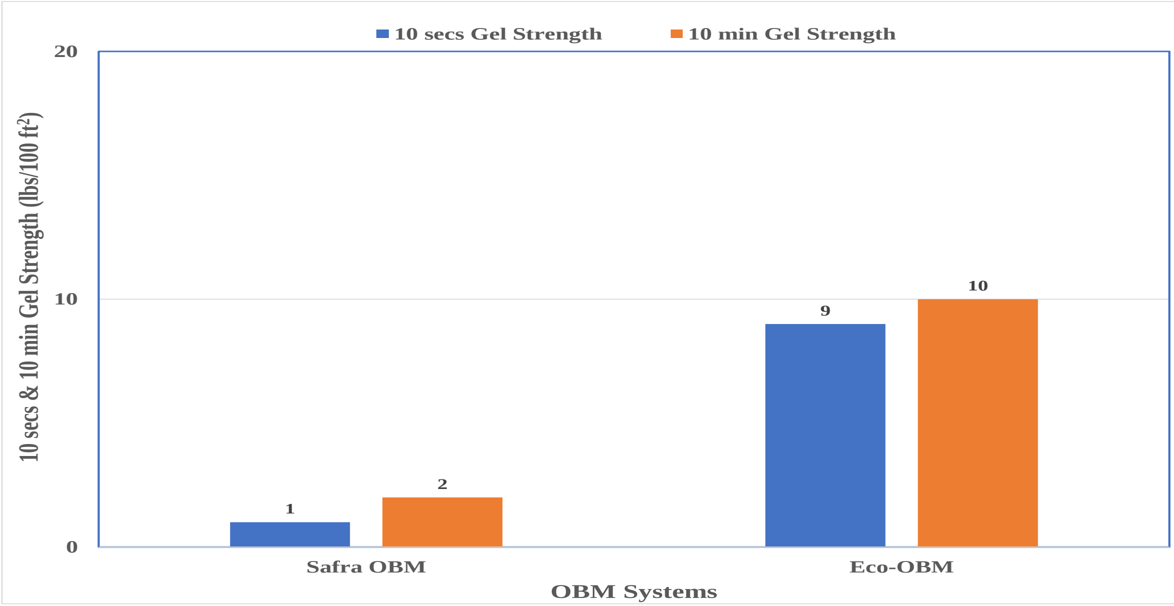

Figure 11 10 secs and 10 min Gel Strength of Safra Oil and the WCO-based Eco-OBM System

Figure 11 shows the 10 seconds and 10 minutes gel strength of the safra oil and the WCO Ester-based Eco-OBM systems. The gel strength of drilling mud indicates the strength of the network created by the electrically attractive charged particles after the cessation of circulation to keep the drill cuttings and other mud solids in suspended condition and avoid any settling, sagging, bridging and cuttings bed formation in the wellbore. Typically, a 10 secs gel strength in the range of 8-12 lbs/100 ft^2 and a 10 minutes gel strength in the range of 10 to 15 lbs/100 ft^2 are desirable for effective cuttings suspension and preventing barite sagging and other solids settlement during the non-circulation period of drilling operation. The results shown in Figure 11 clearly indicate poor gel strength characteristics for the safra oil-based mud at the same amount of viscosifier loading (see Table 1). It indicates the requirement of much higher amount of viscosifier for the safra oil-based mud to generate gel strength above 8 lbs/100 ft^2. The WCO ester-based Eco-OBM system shows the 10/10 gel strength equal to 9 to 10 lbs/100 ft^2 which is within the desirable range. Hence, it clearly demonstrates the potential of formulation of a viable Eco-OBM system using waste cooking oils available from various sources.

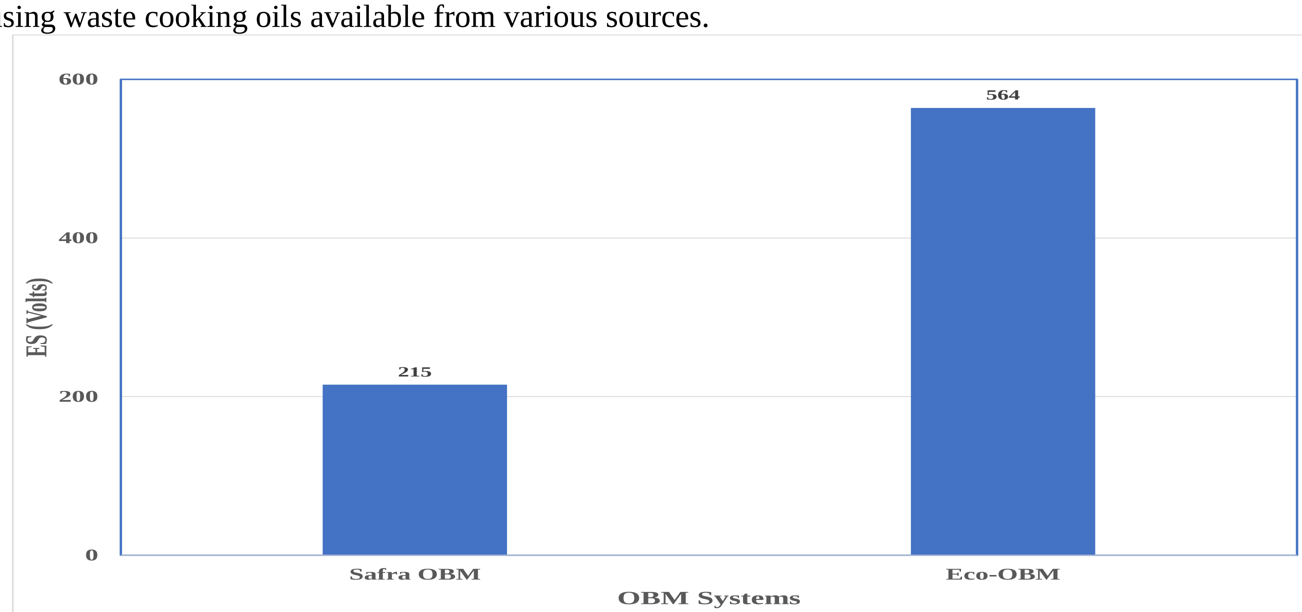

Figure 12 ES (Electrical Stability) of Safra Oil and the WCO-based Eco-OBM System

ES (Electrical Stability) of oil-based drilling mud is one of the critical properties that indicate the tightness of the emulsion and the oil wetting characteristics of the OBM system and thus the physiochemical stability of the OBM. It shows the voltage required to flow the current through the mud due to the creation of a conductive bridge between the two electrodes of the ES measurement device. The conductive bridge is composed of the aqueous fluid and the particulate material of the mud system. Quick and easy formation of the conductive bridge indicate lower emulsion stability and higher possibility of phase separation of the oil-based mud. Hence, the functional capability of the OBM system will be reduced dramatically leading to various borehole problems.

Figure 12 shows the measured ES values of the safra oil-based mud and the WCO ester-based Eco-OBM system. The data clearly shows higher ES value for the Eco-OBM system compared to the safra oil-based mud. Hence, the Eco-OBM system has stronger emulsion and thus higher emulsion stability and better oil wetting characteristics compared the Safra oil-based mud. High ES value of the Eco-OBM system ensures no or reduced possibilities of phase separation during static condition and thus expected to fulfill its functional tasks to prevent mud related drilling problems.

Reusing for an Ecofriendly Spotting Fluid Development

Pipe sticking while drilling is one of the major drilling challenges faced by the oil and gas industry. Some of the critical factors that can trigger a pipe sticking problems are improper drilling practices, poor hole cleaning, borehole instability, excessive reaming or back reaming, improper mud rheology, deposition of thick and poor-quality mud cake, presence of a high permeable formation, etc (Hunter et al., 1978, Aadnoy et al., 1999, Amanullah and Tan 2001, Amanullah 2002). Once a pipe is stuck, different types of aqueous and non-aqueous spotting fluids are used to rescue a stuck pipe. Conventional spotting fluids are commonly designed using diesel, mineral oils or base stocks derived from these oils. Due to the negative environmental characteristics, poor biodegradation properties and also toxic nature, these base oils have severe restrictions for sensitive environments in many parts of the world. Therefore, the industry needs an eco-friendly base stock to formulate green spotting fluids to overcome the limitations of non-eco-friendly spotting fluids used by the industry. Bearing this in mind, the WCO ester was used to formulate a green spotting fluid to recover a stuck pipe without any damage and degradation to the surrounding environments. Table 2 shows the formulations of two diesel-based spotting fluids (Spotting Fluid A and B) and the WCO Ester-based green spotting fluid (WCO Ester Spot). The conventional diesel oil-based spotting fluids were used to compare the performance of the newly developed ecofriendly spotting fluid with respect to the performance of these two traditional spotting Fluids.

Table 2 Formulations of Spotting Fluids A, B and WCO Ester Spot

Spotting Fluid A		**Spotting Fluid B**		**WCO Ester Spot**	
Component	**Amount (cc)**	**Component**	**Amount (cc)**	**Component**	**Amount (cc)**
Diesel	224	Diesel	224	WCO Ester	224
EZ Spot	28	Pipe-Lax	28	EZ Spot	28
Water	98	Water	98	Water	98

A patented method described in US patent #10472958 (Amanullah and Alsubaie, 2019) was used to determine the sticking bond modulus (SBM), and the ultimate sticking bond strength (USBS) of a 10 mm thick mudcake, deposited by a weighted KCl polymer mud. A detailed description and the definitions of SBM and USBS can be found in Amanullah and Al-Arfaj (2017).

The mudcake was prepared by running a filtration test for more than 48 hours at 100 psi pressure and at an ambient temperature. The first test was done in the absence of any spotting fluid to use as the bench mark or base line value. Then the tests were conducted after 16 hours of soaking time of the mudcakes in Spotting Fluids A, B and the WCO Ester spot. Though the requirement of soaking time to complete the interactions varies depending on the compositional variation of the spotting fluids, usually more than 12 hours of soaking time is required for effective interactions of the mudcake and the spotting fluid to destroy the adhesive-cohesive bonds formed by the mudcake. All tests were conducted using mudcake of a similar thickness and deposited by the same drilling mud, i.e., weighted KCl polymer mud.

Figure 13 shows the SBM values of the base mudcake and the mudcakes after 16 hours soaking and interactions with the spotting fluids. Spotting Fluid A shows about 42% reduction of the SBM with respect to the SBM of the base mudcake. Spotting Fluid B shows about 20% reduction of the SBM with respect to the SBM of the base mudcake. The ecofriendly WCO Ester-based spotting fluid shows about 31% reduction of the SBM with respect to the SBM of the base mudcake. Its performance is somewhat lower than the Spotting Fluid A but better than the performance of the Spotting Fluid B.

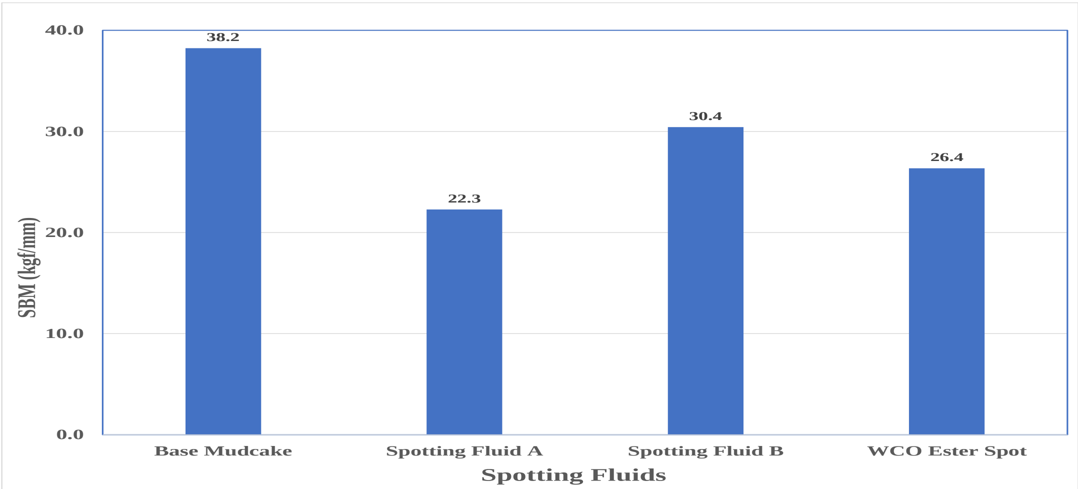

Figure 13 SBM of Original and Spotting Fluids Treated Mudcakes Deposited by a Weighted KCl-Polymer Mud

Figure 14 shows the USBS of the base mudcake and the mudcakes after 16 hours soaking and interactions with the spotting fluids. Spotting Fluid A shows about 75% reduction of the USBS with respect to the USBS of the base mudcake. Spotting Fluid B shows about 70% reduction of the USBS with respect to the USBS of the base mudcake. The ecofriendly WCO Ester-based spotting shows about 73% reduction of the USBS with respect to the USBS of the base mudcake. Its performance is similar to the spotting fluid A (see Figure 14).

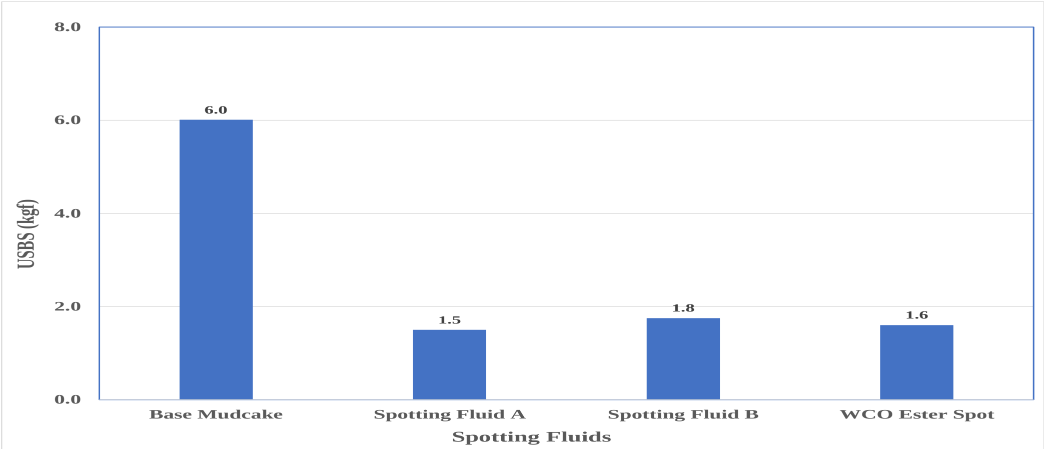

Figure 14 USBM of Original and Spotting Fluids Treated Mudcakes Deposited by a Weighted KCl-Polymer Mud

Conclusions

- Huge amount of food wastes is generated each year around the globe that could be the potential sources of green raw materials for various value-added product development for different industrial applications and thus can play a highly positive role in conserving the natural and edible food resources used as raw materials for various industrial application.
- Promotion of circular economy model and circular product development process as an alternative to linear economic model will mitigate the dependency on non-renewable and finite source materials to provide a sustainable growth and development for the global communities.
- Strategic policies on waste minimization, recycling and reusing of various food wastes will contribute to lower the carbon emission and safeguard the global environment for generations to come.
- The recycling and reusing aspect of circular economy will play an important role in the growth of the existing industries and infrastructures, development of new industries and biorefineries, creation of new job opportunities and conserve the global environments and ecosystems. It will also contribute in the local, regional and national economical development to create a positive societal impact and boost the community development.
- Circular Economy associated with the recycling and reusing of huge volume of green food wastes can solve the technical and environmental problems of various industries to create a highly positive impact on economy, environment and businesses.
- WCO-based ecofriendly lubricant will reduce the COF of water-based muds to mitigate torque and drag problems encounter while drilling deviated, horizontal and vertical wells with high dogleg severity without any detrimental impact to the surrounding environments and the ecosystems.
- Lubricity improvement and the COF reduction of water-based mud (WBMs) due to the incorporation of WCO derived green lubricant demonstrate the potential of reusing of WCOs in oil and gas field applications.
- Preliminary formulation, testing and evaluation of a WCO Ester-based Eco-OBM system demonstrated the potential of development of a green mud system by recycling the WCO to explore and exploit oil and gas resources without any detrimental impact on terrestrial, coastal and marine environments and the ecosystems.
- Excellent YP, gel strength and LSYP values of WCO ester-based Eco-OBM system at very low viscosifier concentration demonstrated its superior performance compared to the safra oil-based mud.
- Testing and assessment of the SBM and the USBS of mudcake after soaking in Spotting Fluids A, B and the WCO Ester Spot demonstrated similar performance for the WCO-based spotting fluid compared to the performance of the traditional diesel-based spotting fluids A and B.
- Ecofriendly WCO Ester-based spotting fluid will facilitate stuck pipe recovery operation without any negative impact on the surrounding environments and the ecosystems.
- Recycling and reusing aspect of circular economy could be a powerful catalyst for localization of product development to increase local content in various industrial applications, conserve finite source natural resources, decentralize the industrial development to contribute in local and regional development.

Acknowledgement

The authors cordially acknowledge the support of UITC management to publish the paper.

References

1. Aadnoy, B.S., Larsen, K. and Berg, P.C. (1999): “Analysis of Stuck Pipe in Deviated Boreholes,” SPE paper 56628, presented at the SPE Annual Technical Conference and Exhibition, Houston, Texas, October 3-6, 1999.
2. Althumiri, N.A.; Basyouni, M.H.; Duhaim, A.F.; AlMousa, N.; AlJuwaysim, M.F.; BinDhim, N.F. (2021), Understanding Food Waste, Food Insecurity, and the Gap between the Two: A Nationwide Cross-Sectional Study in Saudi Arabia. Foods 2021, 10, 681. https://doi.org/10.3390/ foods10030681.
3. Amanullah, M. and Tan, C.P. (2001): “A Field Applicable Laser-based Apparatus for Mud Cake Thickness Measurement,” SPE paper 68673, presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, April 17-19.
4. Amanullah, Md. (2002): “Experimental Determination of Adhesive-Cohesive Bond Strength (ACBS) and AdhesionCohesion Modulus (ACM) of Mud Cakes,” SPE paper 77198, presented at the IADC/SPE Asia Pacific Drilling Technology Jakarta, Indonesia, September 8-11, 2002.
5. Md. Amanullah (2016): Coefficient of Friction Reducing Efficiency of ARC Eco-Lube. IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition held in Singapore, 22–24 August.
6. Md. Amanullah and Mohammed K Arfaj (2017): ARC Eco-Lube-A Food Industry Waste-based Green Lubricant. Abu Dhabi Int. Petro. Exhib. & Conf., Abu Dhabi, UAE, 13-16 November, SPE-188910-MS.
7. Md Amanullah, Turki Thuwaini Mohammed Alsubaie (2019): Determining spotting fluid properties. US Patent #10472958, Date of Patent: November 12.
8. Amanullah, MD., Mohammed Arfaj and Jothibasu Ramasamy (2019): Waste Cooking Oil- A Potential Source of Raw Material for Localization of Green Products Development. Saudi Aramco Journal of Technology, Spring 2019, Lead Article.
9. Md. Amanullah (2005), Physio-chemical characterization of vegetable oils and preliminary test results of vegetable oil-based muds. SPE/IADC Middle East Drilling Technology Conference & Exhibition, 12-14 September, Dubai, U.A.E., SPE-97008-PP.
10. Arjun B. Chhetri, A.B., Watts, K. Ch. and M. Rafiqul Islam, M.R. (2008): Waste Cooking Oil as an Alternate Feedstock for Biodiesel Production. Energies 2008, 1, 3-18; DOI: 10.3390/en1010003.
11. Avinash, A. and Murugesan, A. (2018): Prediction capabilities of mathematical models in producing a renewable fuel from waste cooking oil for sustainable energy and clean environment. Fuel, Volume 216, 15 March, Pages 322-329.
12. Becker, T.E., Azar, J.J. and Okrajni, S.S. 1991. Correlations of Mud Rheological Properties with Current Transport Performance in Directional Drilling. SPEDE (Mar) 16-24
13. Bern, P.A., Zamora, M., Slater, K.S. and Heam, P.J. (1996). The Influence of Drilling Variables on Barite Sag. SPE Annual Technical Conference, Denver, October 6-9, Paper # SPE-36670-MS.
14. Caldeira C., Corrado S., Sala S (2017): Publications Office of the European Union; Luxembourg (Luxembourg): 2017. Food waste accounting - Methodologies, challenges and opportunities, EUR 28988 EN; p. JRC109202.
15. Chhetri A.B, Watts, K. C. and Islam, M.R. (2008): Waste Cooking Oil as an Alternate Feedstock for Biodiesel Production. *Energies* 2008, *1*(1), 3-18; https://doi.org/10.3390/en1010003
16. The Economist. 2017. Food sustainability index. https://foodsustainability.eiu.com/
17. Dahiya, S., Kumar, A.N., Shanthi Sravan, J., Chatterjee, S., Sarkar, O., Mohan, S.V., 2018. Food waste biorefinery: Sustainable strategy for circular bioeconomy. Bioresour. Technol. 248, 2–12. https://doi.org/10.1016/J.BIORTECH.2017.07.176
18. Dosunmu A, Ogunrinde J., (2010): Development of environmentally friendly oil-based mud

using palm oil and groundnut oil. 34th Annual International Conference and Exhibition, Nigeria; July 31 – August 7, SPE 140720.
19. EMF (2013): Towards the Circular Economy, Vol.1, (Ellen MacArthur Foundation), Cowes, Isle of Wight.
20. EPA (2011): (http:/www/epa/gov.region9/waste/biodiesel/questions.html), August.
21. Ezzat AM, Al-Buraik KA (1997): Environmentally acceptable drilling fluid for offshore Saudi Arabia. SPE 37718. Paper Presented at the SPE Middle East Oil show and conference, Bahrain, 15 -18 March.
22. The European Parliament News (2021): Circular economy: definition, importance and benefits. Updated March 3. https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits
23. FAO. 2011. Global Food Losses and Waste. Extent, Causes and Prevention (available at http://www.fao.org/docrep/014/mb060e/mb060e00.pdf).
24. Growcock, F. B., Frederick, T.P., Reece, A.R., and Green, G.W., (1999): Novel Lubricants for Water-Based Drilling Fluids. SPE International Symposium on Oilfield Chemistry, February 16-19, 1999, Houston, Texas.
25. Gui, MM, Lee, KT, Bhatia, S. (2008): Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy 33(11): 1646–1653.
26. Hunter, D., Baroid, N.L. and Adams, N. (1978): "Laboratory and Field Data Indicate Water-base Drilling Fluids that Resist Differential Pressure Pipe Sticking," OTC paper 3239, presented at the Offshore Technology Conference, Houston, Texas, May 8-11.
27. Kaza, S., Yao, L., Bhada-Tata, P. and Woerden, F.V. (2018): What a Waste 2.0 – A Global Snapshot of Solid Wastes Management to 2050. Urban Development Series. World Bank Group.
28. Lin C.S.K., Pfaltzgraff L.A., Herrero-Davila L., Mubofu E.B., Abderrahim S., Clark J.H., Koutinas A.A., Kopsahelis N., Stamatelatou K., Dickson F., Thankappan S., Mohamed Z., Brocklesbyc R., Luque R., (2013). Food waste as a valuable resource for the production of chemicals, materials and fuels. Current situation and global perspective. *Energy Environ Sci.* 6:426–464. doi: 10.1039/c2ee23440h.
29. McCarthy, A., R. Dellink and R. Bibas (2018), "The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches", OECD Environment Working Papers, No. 130, OECD Publishing, Paris. http://dx.doi.org/10.1787/af983f9a-en.
30. Mondshine, T.C. (1970): "Drilling-mud lubricity: Guide to reduced torque and drag," The Oil and Gas Journal, December 7, pp 70-73.
31. National Geography (2016): https://www.nationalgeographic.com/magazine/article/global-food-waste-statistics. Published March 1.
32. Okrajni, S.S. and Azar, J.J. 1986. The Effects of Mud Rheology on Annular Hole Cleaning in Directional Wells. SPEDE (August) 297-308.
33. Redburn, M., Dearing, H. and Growcock, F. (2013): Field Lubricity Measurements Correlate with Improved Performance of Novel Water-Based Drilling Fluid. 11th Offshore Mediterranean Conference and Exhibition in Ravenna, Italy, March 20-22.
34. Salimi E., Taheri M.E., Passadis K., Novacovic J., Barampouti E.M., Mai1 S., Moustakas K., Malamis D., Loizidou M. (2020): Valorization of restaurant food waste under the concept of a biorefinery. *Biomass Convers Biorefin.* doi: 10.1007/s13399-020-00613-4.
35. Sanchez G, Leon N, Esclapes M, Galindo I, Martinez A, Buizual J, Siegert I. (1999): Environmentally safe oil-based fluids for drilling activities. SPE/EPA Exploration and Production Environmental conference, Austin; Texas, 28 February–3 March, SPE 52739.

36. Sodhi, A. K., Tripathi, S., & Kundu, K. (2017). Biodiesel production using waste cooking oil: a waste to energy conversion strategy. Clean Technologies and Environmental Policy, 19(6), 1799–1807. doi:10.1007/s10098-017-1357-6.
37. Tsai, W.-T. (2019). Mandatory Recycling of Waste Cooking Oil from Residential and Commercial Sectors in Taiwan. Resources, 8(1), 38. doi:10.3390/resources801003.
38. UNIDO (2017): Circular Economy. https://www.unido.org/sites/default/files/2017-07/Circular_Economy_UNIDO_0.pdf.
39. United Nations (2018). Ensure Sustainable Consumption and Production Patterns. Available online: https://unstats.un.org/sdgs/metadata/files/Metadata-12-01-01.pdf, 14 Feb.
40. World Economic Forum (WEF, 2020): Circular Economy: Definition, Principles, Benefits and Barriers. https://youmatter.world/en/definition/definitions-circular-economy-meaning-definition-benefits-barriers/, updated on February 21.
41. Yassin AAM, Kamis A, Abdullah MO, (1991): Formulation of an environmentally safe oil-based drilling fluid. SPE Asia-Pacific conf. 4–7 Nov., Perth, Australia; 1991. https://doi.org/10.2118/23001-MS.