Advanced Biofuels Program

Global concern for energy security and climate security issues made it imperative for the scientists to explore the production of clean fuel from renewable sources in sustainable manner. Advanced biofuels do not rely on fossil resources and thus present a renewable alternative to conventional petroleum based fuels. Advanced biofuels can be produced from next generation non edible feed such as lignocellulosic biomass, agricultural residues, aquatic weeds, algae and organic waste. In order to make this process economically viable at a commercial scale, it is essential to integrate this process with production of high value bio commodities in a bio-refinery approach. To achieve sustainability and to address climate change issues, advanced biofuels division is exploring development of clean technologies for biofuel and biocommodity production from 2nd and 3rd generation feed such as algae, aquatic plants and used cooking oil (UCO), under **DBT-TERI Center of Excellence project on 'Integrated production of advanced biofuels and biocommodities'.** To assess the long term viability of these processes, comprehensive techno-economic analysis, environmental assessment and socio-economic assessment are also being studied.

Based on the research thrust this division's research themes categorized under two areas; '***Microbial biofuels & biochemicals***' and '***Pyrolytic biofuels, biochar & green chemicals'***.

Microbial Biofuels and Bio-chemicals Area

The research activities of 'Microbial biofuels and Biochemicals' concentrates on development of bio-based renewable technologies for production of advanced biofuels; biohydrogen, bioethanol, biomethane, biobutanol including third generation algal biofuel and biochemicals; second generation 2,3 Butane Diol, neutraceuticals, high value organic acids, in an integrated manner by using microbe(s) and algae as cell factory.

Algal cultivation for feed development for advanced Biofuels and Bio-commodities production at a large scale (100,000 l)

Microalgae are one of the promising options for renewable fuel production in future. Microalgae have the potential to mitigate carbon emissions and to reduce crude oil imports. To realize the economic viability, production of biofuels from microalgae, should be combined with biocommodities in an integrated manner. With intensive research explorations an area of 220 sq. meter (100,000 L) marine algal production system has been established near Mumbai coast last year with the objective of producing algae as next generation feed for advanced biofuel (biodiesel, Pyrolytic oil and biohydrogen production). This microalgal cultivation system is based on a sunlight-distributed improved productivity system that is integrated with downstream processing units consisting of settling tank and lipid extraction unit along with on-site set up for R&D laboratory. With an objective to recover lipid with high recovery efficiency at low cost, intensive research explorations are being carried including process developed for lipid extraction directly from wet algae (without sun drying that requires large areas of land). The lipid extraction unit installed at the Mumbai project site has the capacity to process 5–7 kg/h of wet algae. The deoiled algae after lipid extraction is being tested for possible application as feed for production of value added commodities such as animal feed, aqua feed, biodegradable food packaging plastics, platform chemicals, nutraceuticals, biohydrogen, and pyrolytic bio-oil.

Marine algal production system in Mumbai (220 sq. meter/100,000 L)

Biohydrogen production from aquatic plant (Water hyacinth and *Azolla*) and microalgae biomass

Aquatic plants and algal biomass are being tested as next generation feed for biohydrogen production though use of select C5 and C6 sugar utilizing microbes.

Water hyacinth is an aquatic invasive species that multiplies vary fast in the wetlands. It is estimated that Water hyacinth is covering more than four million hectares of freshwater surface in India, leading to generation of 450 tonnes of water hyacinth biomass (wet weight) per hectare per year. Rapid colonization of negatively this weed prevents sunlight from reaching surface of water thus imparted growth of the flora, fauna and microbes. To ensure ecosystem sustenance it is thus essential to remove this weed from water bodies regularly, putting increase financial pressure on the municipal bodies. Water hyacinth's biomass contain more than 50% carbohydrates (on dry weight basis) and thus gained attention as possible feed for the production of biofuel. The dried biomass can be used as feed after pre-treatment and enzyme hydrolysis. Acid pre-treated can be used biomass for hydrogen production by using *Enterobacter cloacae* strain DT-1 as host. The process for biohydrogen production from acid pre-treated water hyacinth biomass (rich in pentose sugar) was up scaled in 30 litre and subsequently in 150 litre bioreactor.

Scale up of biohydrogen production from acid pretreated water hyacinth hydrolysate in 30 liter bioreactor

Scale up of biohydrogen production from acid pretreated water hyacinth hydrolysate in 150 liter bioreactor

Azolla species is one of the fastest growing aquatic fern that can grow in contaminated water and has potential for generation of substantial biomass. *Azolla* sp. has high biomass productivity potential (12 ton/ha/year). Major fraction of this biomass include lipid and carbohydrates (50-55%, cellulose, hemicellulose, starch), protein (25-30%), essential amino acids and thus it has the potential to be used as feed for production of clean fuels and bio-commodities (aqua feed, animal feed, bio fertilizer, etc.).

Large scale cultivation of *Azolla* in outdoor ponds in TERI GRAM

Azolla cultivation has been carried out in large scale outdoor ponds and the sun dried *Azolla* biomass was processed for acid pre-treated and enzyme hydrolysis for conversion to monomeric fermentable sugar. This fermentable sugar was used as feed for biohydrogen production. Biohydrogen production from acid pre-treated Azolla biomass sugar (pentose stream) was up scaled in 10 litre scale by using *E. cloacae* strain DT-1.

Possibility of using deoiled algae for hydrogen production is being tested.

Bioethanol production from 1st and 2nd generation feedstock

Bioethanol has got wide attention as an alternative transport fuel owing to its positive impact on environment and its potential to reduce dependence on conventional fossil fuel. With an aim to develop technologies for bioethanol production from the first and second generation feedstock, bioethanol production from a range of feed stock is being explored. Intensive research explorations paved the way for development of bioethanol production in 10 litre scale from low cost commercial grade sugar by a newly isolated novel strain, *Candida tropicalis* TERI DC. Further a co-fermentation process has been developed for bioethanol production from water hyacinth and corn cob biomass through use of *Pichia stipitis* and *Candia tropicalis* TERI DC as microbial cell factory. With proof of concept established, the process will be studied at Pilot scale.

Scale up of bioethanol production from low cost industrial grade sugar/sugarcane black strap molasses novel yeast isolate; *Candida tropicalis* strain TERI-DC

Enhanced methane recovery from livestock waste

Livestock waste is one of the major greenhouse gas sources and cattle manure is one of the major livestock organic solid waste that has high COD content. Hence, it is imperative to treat this organic waste and to tap the high energy content from this waste prior to discharge into the environment. With an aim to enhance energy recovery in the form of methane and to enhance rate of biomethane production, research explorations of this area focused on development of efficient biomethane production by modulating the dynamics of complex microbial consortia. This process was successfully up scaled in 20 litre scale. This process resulted in lowering the Hydraulic Retention Time (HRT) of the process with increase in volumetric biogas production and increase in methane production efficiency of biogas process.

High value Biochemical production

Fermentative production of 2,3 Butane Diol from glycerol, the co-product from biodiesel trans esterification process

2,,3-Butane Diol (2,3-BD) is a specially chemical with reported applications in several industries. It is used as a precursor molecule for synthesis of range of chemicals (1,3-butadiene, butanes, methyl ethyl ketone (MEK), gamma butyrolactone, diacetyl, esters etc.). These downstream products have applications in chemical industries; fuel additive, textiles, polymers, synthetic rubbers and plastics, etc.

With a goal towards zero-waste discharge, this area is also researched with possibility to develop microbial process for production of 2,3 Butane Diol from glycerol, the co-product from algal biodiesel trans esterification process. The bioprocess for 2,3 Butane Diol production from glycerol and low cost commercial grade sugar has been developed using two selected microbes; *Enterobacter roggenkampii* strain TERI CT and *Klebsiella pneumoniae* strain RA1 (newly isolated non-pathogenic strains isolated by Research Team at TERI), respectively . Laboratory scale process for downstream purification of 2,3 BD from low cost commercial grade sugar and glycerol based fermentation broth has been developed.

Scale up of upstream fermentation process and downstream 2,3 BD purification process is under progress.

TERI's downstream processing laboratory

Pyrolytic Biofuel, Biochar and Green Chemicals

Development of technology for Production of Biodiesel From Mixed Oil (algal lipid and Used Cooking Oil (UCO)

Most of the established biodiesel plants are based on a particular type of feedstock oils. However, it will be beneficial to develop process model for different types of feedstock mix so as to attain the feedstock sustainability.

Under DBT-TERI-Centre of Excellence of Biofuel and Bio commodity two indigenous processes have been developed in TERI for two stage trans-esterification of Used Cooking Oil (UCO) and a pilot scale unit of 10kg/h capacity is established. The processes, completely eliminates use of water for biodiesel purification and thus is more sustainable. The prime objective is to develop models based on primary research data generated at a scale which will be suitable for production and quality prediction of biodiesel from any type of mixed oil. Process steps have been established for conversion to BIS-VI compliant biodiesel with respect to properties such as purity, cetane value, oxidization stability, cold flow properties and calorific value.

TERI's Process 1 conversion efficiency (98-99 %) is greater than literature reported benchmark for UCO conversion (65-97%), whereas, TERI's Process 2 conversion efficiency is 95-97 %. The electricity consumption per unit of biodiesel produced is <0.5 kWh.

Fig. 1: TERI's 10kg/h Biodiesel Pilot Test Unit

Development of Technology for Pyrolytic Biofuels

TERI has developed an indigenous pyrolysis technology for making refinery grade bio oil and biochar from different agro-industrial biomass residues. The Patented Pilot Scale Pyrolysis Test Unit (PTU of capacity 20 kg/h) is an uniquely designed fully automated Programmable Logic Control (PLC) based gas fired auger pyrolyser reactor system. The Pilot Reactor has been tested extensively with non-edible oil seed residues e.g. Jatropha, Karanja other biomasses such as Sugarcane Bagasse, Paddy straw, Cotton stalks, Ground nut shell, Mustard stalk, Wheat and Maize stalk, Cashew nut-shells and Lignin residues from lingo-cellulosic ethanol plant.

A catalytic pyrolysis process has been established for downstream catalytic upgradation of pyrolytic vapour produced in the non-catalytic pyrolyser over indigenously made novel catalysts for improving bio oil characteristics in terms of Oxygen content (<5%) and H:C ratio. This upgraded oil is intended to be co-processed in refinery or could find possible direct applications as alternate transport fuel. The integrated 2-stage catalytic cracking and pyrolysis vapor upgrading unit reactor has been commissioning for testing of pyrolysis vapor over stage-I & stage-II catalysts. Chemical and physical characterization of the oils indicates high degree of up-gradation w.r.to Oxygen content and heating value.

Fig. 2: TERI's 2-Stage Catalytic Cracking and Pyrolysis Vapor Upgrading Unit

Dry algal (*Scenedesmus*, *Spirullina*, and *Chlorella*) biomass has been processed in the 10 kg/h continuous pilot reactor and the bio oil is upgraded to transport grade biofuels through catalytic route by separating the valuable chemicals. In-house green catalysts has been synthesized for ex-situ drying of wet algal paste as an alternative to electrical drying.

Industrial Wastes to Green Char and Value-added Chemicals

With the objective of using industrial waste for value added product formulation, pyrolysis technology has been developed for production of commercial grade biochar, chemicals (Phenols, Catechol etc) from Industrial wastes Solvent Extracted Catechin (SEK) & Cutch Waste.

The waste from the Indian Wood Products (IWP) Company Ltd. has been explored to produce value added chemicals in pilot scale. Phenol / catechol and Activated carbon are the two major pyrolysis products formed that have high economic values. An innovative method of drying of wet Liquor has been developed by using low cost Catalysts (Cat-I & Cat-II) as drying agent. Under Catalytic drying overall yield of biochar are found to be 35-48 wt. % for different waste streams where phenolic compound are produced between 74-85 wt. % of biooil. This biochar is suitable for heating applications and also would be explored as soil amender. The highly microporous activated carbon produced through downstream activation of biochar using environmentally benign green chemicals has high Brunauer-Emmett-Teller (BET) surface area 900-1200 m2/g thus having future potential for gas purification as well as water purification applications. TERI is presently working on Phase-III pyrolysis technology demonstration in IWP.

Fig.3a: Phenol and Catechol Derived by Pyrolysis of IWP Plant Wastes

Fig 3b: Pyrolytic Biochar from IWP Plant Waste (prior to activation)

Value added biocommodity production from algae

Fish is rich in beneficial polyunsaturated fatty acids, vitamins and is an excellent source of protein. With increasing health awareness and fish being a staple food in many regions, overfishing has resulted in insufficient recovery and dwindling of fish stocks becoming a global problem. One of the main components in rearing fish, is the fish meal, Initiative has been taken to improve the quality of fish meal at an affordable price. Appropriate feeding will result in getting more and better quality of flesh and oil. Algal co-products have shown potential for fish meal formulation. Substitution of fishmeal with algae biomass aids in increasing omega 3 fatty acid content, taste improvement, growth rate increase of the fish. Hence, the algae biomass is explored for aqua feed formulation and large test set-ups have been established for trail runs of this aqua feed formulation with various combinations of ingredients in experimental feed diets for fish like, tilapia, Pearls spot, common carp, Rohu and Catla.. Compositional analyses of formulated feeds have shown positive growth and high potential for development of a commercial aqua feed.

Figure. Experimental fish tank set-ups for aqua feed development housed in the aquaculture center at the TERI Coastal Education Hub

Algae biomass has been explored for production of high value carotenoid and Poly Unsaturated fatty Acids (PUFA). Laboratory scale process has been developed for production of lutein and omega-3 fatty acid from *Nannochloropsis oculata* and *Dunaliella tertiolecta.*