Anaerobic Digestion of Micro and Macro Algae, Pre-treatment and Co-Digestion-Biomass — A Review for a Better Practice

R. Paul, L. Melville, and M. Sulu

***Abstract*—Anaerobic digestion (AD) of algae biomass has been investigated since long. However to enhance full scale commercial future prospects of algal bio technology, it is important to develop methods for better utilisation of the algae biomass. For effective AD involving algae biomass, there is still a need for intensifying algae biomass digestion. Pre-treatment practices on micro and macro algae improve the digestibility of the algae biomass and an increase in biogas yield. Co-digestion of algae biomass with BWW, sewage sludge and agricultural waste is a promising sustainable strategy as it enhances AD and helps in the safe disposal of different wastes. Combining pre-treatment and co-digestion provides a better practice of the AD process. Utilisation of AD of algae biomass, and the potential of AD of algae biomass with three co-digestion feedstock –Sewage sludge, spent grain and agricultural waste are further discussed. This paper concludes that AD can act as a better 'connecting link' in the algae bio technology providing economic viability and sustainable practice.**

***Index Terms*—Anaerobic digestion, algae biomass, co-digestion, pre-treatment.**

I. Introduction

Conversion of biomass into renewable energy has been one of the key areas of research for the past few decades. A large body of research has been published on renewable energy from algae – micro and macro, which have become a representative of biomass resources with great bio diversity and variability in their biochemical composition [1]. It becomes a sustainable option for AD due to its high presence of starch, proteins and lipids and lack of lignin [2], [3]. Developing research on algae biomass has both economic and environmental sustainability concerns which involve operational efficiency, minimization of environmental impact and socio-economic considerations [4]. To enhance full scale commercial future prospects for algal bio technology, it is then important to develop methods to enhance the valorisation of the algae biomass. AD, a spontaneous process mediated by the micro-organisms does not require cost intensive advanced dewatering or further chemical extraction processes for energy generation from the digested algae biomass. However to increase the utilization of AD involving algae biomass, current research suggests that there is still a need for optimizing algae biomass digestion [5]. Since AD involves the biological degradation of organic matter, adequate pre-treatments favouring disintegration and solubilisation of high molecular compounds can improve biomass degradability [6]. With increased biomass digestion, research reports increased methane production by digesting other organic feedstock with algae biomass by process called as co-digestion [7]. Therefore, AD can act as a 'connecting link' in the algae biotechnology providing economic viability and sustainable practice by incorporating effective substrate pre-treatment and co-digestion practices.

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The authors are with Birmingham City University, Millennium Point, Birmingham, UK (e-mail: Roshni.Paul@bcu.ac.uk, Lynsey.Melville@bcu.ac.uk, Michael.Sulu@bcu.ac.uk)

II. Algae Biomass Utilization for AD — Review of Prospects and Challenges

Biomass as a renewable energy source is referred to living and recently dead biological matter that can be used as fuel or industrial production [8]. The term algae refer to both macro and micro algae. Algae biomass which mainly constitutes of carbohydrates, lipids and proteins is utilised for bio-energy production. Macro algae form multi cellular thallus whereas microalgae are microscopic of size 5-50 µm which grow in salt or fresh water [3]. AD technology which has been deployed in the wastewater industry in the UK for many decades has the potential to reduce greenhouse gases emissions from the integrated processes, improve energy security, produce clean bio-methane gas, fertilizer, and decentralized electrical and thermal energy and thereby achieve self-sufficiency in waste treatment, energy generation and resource use [9]. Environment Agency (UK) reports that AD is very well established in the UK as a waste treatment technology for sewage sludge and is also supported as one of the ways of diverting biodegradable wastes from landfill. In terms of environmental impact, the energy recovery and recycling achievable through AD makes it a potential way to treat bio wastes [10].

AD of microalgae first mentioned by Golueke *et al*. (1957) addressed processing of microalgae biomass grown in waste water treatment ponds. Several studies thereafter in the later decades have confirmed that algae biomass can be anaerobically digested to produce biomethane [11]. Literature also recommends AD as a versatile technology platform which can potentially serve both industry and society in useful ways [12]. As AD process is appropriate for high moisture content (80-90% moisture) organic wastes, points out that it can also be very useful for wet algal biomass [4]. Zammaloa *et al*. (2009) argues that AD is therefore an attractive waste treatment practice in which both pollution control and energy recovery can be achieved [3]. It can be thus combined with renewable energy source like algae biomass to form a

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potential low carbon technology. Agricultural and industrial wastes have already become ideal candidates for AD because of the high level biodegradable materials they contain. In comparison, the positive aspect of algae AD is the fact that the resulting biogas has high energy content and also that it does not contain sulphur which causes engine corrosion. The presence of lipids in the microalgae enhances the biogas production and the 'bio scrubbing' potential of microalgae by removing CO_2 from the biogas produced also enriches the biogas making the technology plausible [3]. Microalgae biomass is a sustainable option for AD due to its high presence of starch, proteins and lipids and lack of lignin [2], [3] The production of oil from algae range from 5.87L/m2 to 13.69L/m2 which is 10-23 times greater than that of the highest oil producing terrestrial oil crop, palm. Also that, the land requirement is 10-340 times smaller than that of the other terrestrial counterparts [13]. But the major disadvantage of the microalgae biomass is the high expenditure for infrastructure and the considerable energy requirements for harvesting, dewatering and associated downstream processes of the relatively diluted algae cultures [14]. Coupling an anaerobic digester to a microalgal culture is one of the promising avenues towards the production of renewable bio energy as it appears to be in an ideal position to address the sustainability challenges associated with the microalgal biotechnology. However, biodegradability of the microalgae can be lower as the biochemical composition and the nature of the cell wall varies. Therefore any physical, chemical or biological pre-treatments applied on the microalgae cells can significantly and efficiently increase the conversion yield of algal organic matter into methane. Nevertheless on an energy balance basis, AD appears to be the optimal strategy for the energetic recovery of cell biomass if the cell lipid content does not exceed over 40% [2].

The strong and renewed interest in the AD now is related to its ability to treat and to convert a wide range of organic wastes into renewable energy which opens up opportunities for co-digestion with algae biomass. However in the specific case of algae biomass, Cameron *et al*. (2011) notes that there still remains the crucial research to assess the potential of these coupled biotechnological processes and help optimize their design, operation and control [15].

III. Algae Biomass as AD Feedstock — Pre-treatment, Co-digestion

Research studies suggests that biomass pre-treatments can be used to increase methane yields as well as to increase the digestibility of the biomass aiding in the recycling of the nutrients during AD [16]. Lee *et al*. (2013) points out that there is still little information regarding the algal pre-treatments that can be applied in AD [17]. Pre-treatments methods practiced include acid pre-treatment, mechanical, enzymatic, microwave, autoclaving, sonication, thermal, electric, free/ thaw and chemical methods [18]. Microwave irradiation also enhanced the disintegration and digestibility of the microalgae [15]. Among these pre-treatments, research by R. Harold *et al*. (2007) reports that the cell wall barrier can be better overcome by sonication [19], [20]. Biomass disintegration improves the solubility of sludge particles and thereby increasing the bio availability. The conversion technology for biofuel production from macro algae is in its early stage. Research indicates that pre-treatment methods can be easier in the case of macro algae as the amount of lignin found in them are lesser when compared to the terrestrial plants. Methods like steam explosion, wet oxidation, hydrothermal treatment, bead milling and plasma assisted methods are examples of pre-treatments adopted for macro algae (e.g. Chaetomorpha linum). Simple, economic pre-treatment methods which make the biomass highly available for the bio-conversion have still to be researched to enhance the biomass utilization [21]. Some examples of microalgae and macroalgae species and the pre-treatments researched are listed in the Table I [22]-[26].

TABLE I: Pre-treatment of Micro/Macroalgae Strains

Microalgae / Macroalgae	Pre-treatment	Reference
Chlamydomonas reinhardtii (Micro) Chlorococcum sp (Micro) Spirogyra (Micro) Chlorella vulgaris (Micro)	Acid Alkali Enzymatic High Pressure Thermal Ultrasound	22 23
Fucus vesiculosus Saccharina latissima Chaetomorpha linum	Mechanical Maceration Hydrothermal	24 25 26

Safe disposal of different wastes generated in the society is a growing concern and it initiates the scientific community to collect and treat the wastes effectively. Khalid *et al*. (2011) argues that the co-digestion practice helps different organisations in providing solutions for managing different wastes generated in the society and also enhancing the anaerobic digestion process in itself. In terms of AD, co-digestion helps to balance the C/N ratio and solve the problem of ammonia toxicity. Yen and Brune, (2007) suggested that the mixing process which is controlled by C/N ratio in co-digestion results in the distribution of concentrated substances, otherwise causing inhibitions during the digestion process. C/N ratio varies according to the organic material, and a desired C/N ratio can be achieved by adjusting a low C/N ratio feedstock with a feedstock that has a higher C/N ratio which is a favourable factor for the co-digestion practice of organic feedstock with algae biomass. Co-digestion is also beneficial because potential toxic ammonia is diluted which allows increased loading rate and improved biogas yield [27].

Anaerobic digestion of bio solids and organic fraction of MSW has been researched in previous years to produce methane. Zhang *et al*. (2008) also suggests that the digestion of nutrient deficient MSW and bio solids can be increased by mixing each other [28]. Further researches have shown that the biogas production was improved for a certain percentage of macro algae and microalgae replaced for sludge. Brewery waste water (BWW) is large in bulk and rich in moisture, making it a suitable co-digestion substrate with microalgae. Option of co-digesting BWW with algae to release energy is encouraging as it is a promising sustainable strategy. Spent grain, a major by-product of BWW is rich in nutrients though the moisture in the spent grains makes it difficult to handle and heavy but when digested with algae biomass could produce high quality biogas. Also it would help the breweries in the safe disposal of the spent grains [29].

Combined process of AD of microalgae biomass with agriculture waste waters is also performed to evaluate the integrated system of combining a microalgal bacterial system for wastewater treatment with anaerobic digestion of the produced biomass. The digestion results show that methane yield was highly influenced by substrate/inoculum ratio and by lipids concentration of the biomass. Several pre-treatment techniques are researched for different species over different conditions. Alzate *et al*. (2012) continues to explain that such different efficiencies are obtained from different pre-treatments as the mechanisms underlying the pre-treatments applied to the microalgae are fundamentally different. In the case of ultrasound, it breaks up the cell by cavitation releasing the intracellular material and promotes chemical reactions due to high local temperatures and pressures, leading to formation of highly reactive radicals (H+ and OH-) which facilitates organic degradation. This accelerates the hydrolysis of the biomass and VFAs are more readily generated through acidogenesis and subsequently transformed to methane, whereas in thermal hydrolysis the heating, pressurisation of the microalgae followed by steam explosion plays key role in biomass hydrolysis although there is a chance of formation of recalcitrant compounds at higher temperatures during thermal hydrolysis which can potentially inhibit the digestion of the biomass [30]. Biochemical composition of micoroalgal biomass also determines the methane yield obtained [31]. Different microalgae species have been tested under various experimental conditions (i.e. nutrient/nitrogen deficiency; nutrient deficiency/sufficiency; heterotrophic conditions) and their lipid content and lipid productivity have been reported. All these species studied have been reported to have been grown in wastewater streams. However a conclusion can be noted from the above discussion that there is no one specific species which is the best for either higher biomass and/or lipid productivity, and it depends on various factors like growth medium, climatic conditions, and thus screening microalgae strains for suitable potential biorefinery applications including biofuel production becomes a relevant research area [32].

The results obtained from the co-digestion experiments indicate that addition of microalgae as a co-substrate increases biogas yield. Also that rupturing of the cell as a result of pre-treatment can also increase CO_2 ratio of the biogas as seen from fermenters fed with ruptured microalgae [33]. To make the system carbon neutral, Ashish *et al*. (2013) suggests that the emerging waste wasters after digestion can also be utilized for the growing of algae utilizing the remaining nutrients, typically inorganic nitrogen and phosphorus [34]. This would also help in the reduction of the production costs and doubling the algae production. The conversion technology for biofuel production from macroalgae is in its early stage. Simple, economic methods which made the biomass highly available for the bio-conversion have been still researched to enhance the biomass utilisation [35]. One of the main hindrances to the macroalgae utilisation is its low energy yield due to toxicity issues and low carbon to nitrogen ratio resulting lower mixing for the process efficiency. In an AD perspective, low nitrogen content with high carbon content results in low biogas yield. However, high concentrations of nitrogen leads to ammonia toxicity and decreases methanogenic activity and further accumulation could completely stop the AD process from proceeding any further. C/N ratio varies according to the organic material and the association of various substrates is a strategy to improve the performance of a digester by ensuring an optimal influent composition and to increase the biogas productivity by optimising the Carbon to Nitrogen ratio (C/N) required for the anaerobic microbes leading to a less inhibition from ammonia release. Speece (1996) found that the C/N ratio if lower than 20, then there is an imbalance leading to nitrogen release and accumulation of VFAs and research by Yen and Brune (2007) showed a significant enhancement of methane production with an addition of waste paper to algal sludge feedstock and the optimum C/N ratio was observed to be between 20 and 25. Co-digestion is beneficial because potential toxic ammonia is diluted which allows increased loading rate and improved biogas yield. The co-digestion practice also helps different organisations in providing solutions for managing different wastes generated in the society and thereby enhancing the anaerobic digestion process in itself [36], [37].

On an energy balance basis, Sialve *et al*. (2009) reports that AD is the optimal strategy for the energetic recovery of algae cell biomass by if the cell lipid content does not exceed over 40%. Similarly, in the case of macro algae AD to produce biogas, macro algae exhibits higher methane production rates than the land based biomass. Conversely to microalgae, the seaweed (e.g. Kelp) doesn't need any pre-treatment because of the non-existence of lignin in its biomass. But unlike microalgae, AD of macro algae is very much affected by species and composition of macro algae, the geographical conditions, and seasons. However, methane production rate is found increasing by means of co-digesting it with manure, and waste activated sludge. AD of macro algae is not yet viable economically due to high costs of macro algae feedstocks which need to be reduced by 75% of the present level [38]. To enhance biogas production and biomass digestion, efficient pre-treatment methods have to be optimized. As AD of algae has been successfully carried out in a laboratory scale focusing on a either regionally available or robust species, there is still the need to improve the efficiency of the process and to search for highly digestible microalgae species to make the technology feasible in a large scale application.

IV. Conclusions

This paper had its focus on the utilisation of algae biomass for AD and the effects of pre-treatment in anaerobic digestion and the application of co-digestion in using today's diverse substrate sources along with algae biomass.

A. The Conclusions That Can be Drawn Are

- Pre-treatment practices on micro and macro algae improved the digestibility of the algae biomass and an increase in biogas yield.

- Co-digestion of algae biomass with BWW, sewage sludge and agricultural waste is a promising sustainable strategy as it enhances AD and helps in the safe disposal of different wastes.
- Combining pre-treatment and co-digestion provides a better practice of the AD process.
- This paper concludes that AD can act as a better 'connecting link' in the algae bio technology providing economic viability and sustainable practice.

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Roshni Paul is a PhD researcher at Birmingham City University. His research topic is in anaerobic digestion of algae biomass, specialising in the feasibility of ultrasound pre-treatment of algae biomass prior to anaerobic digestion. Her research interests include anaerobic digestion, bioenergy, biomass to biofuels and algae. She got the BSc in chemistry, and the MSc in nanotechnology and the M.Ed in education recently.

Lynsey Melville is a reader in bioenergy and the director of the Centre for Low Carbon Research. She is currently leading the bioenergy research group whose focus is on accelerating the adoption of environmentally sustainable and commercially viable energy from biomass. Lynsey is now principle investigator on two large EU funded programmes: Enalgae and Bioennw. She is working closely with the knowledge based engineering group and a broad range of stakeholders the aim of this work is to capture data and information from across the whole bioenergy delivery chain. One of the outcomes of this work will be the development of a number of innovative and adaptive decision support systems which will enable stakeholders to identify optimal sites, partners and markets and develop project plans which will be tailored to regional conditions. Lynsey has previously worked as a process scientist for Severn Trent Water and following her PhD (funded by the Engineering and Physical Sciences Research Council (EPSRC)) established a spin out company from the University of Wolverhampton with two other academics. This company offered consultancy and research and development in the water and wastewater industry.

Michael Sulu began his academic career by completing an M.Eng in biochemical engineering at UCL. He moved from there to complete the M.Res in clean chemical technology at York University and Finally completed his Ph.D. at the University of Birmingham. His doctoral research was in bio-hydrogen production. He bioprocess engineering background lends itself well to projects involving process characterisation, intensification and scale up. His current research interests involve the production of biofuels, the biorefinery concept and the production of energy from waste sources. Currently, he is involved in biorefinery research, UG module/course development, Ph.D. supervision and beginning the process to gain chartership within the IChemE. His specialties are bioprocess characterisation, intensification and scale up. He process engineering. bioprocess problem solving.