Theoretical Estimation of Algal Biomass Potential and Lipid Productivity for Biofuel Production in Ethiopia

Abraham M. Asmare[1], Berhanu A. Demessie[2], Ganti S. Murthy[3]

[1]Lecturer , School of Chemical and Biochemical Engineering, Addis Ababa Institute of Technology, 385, Ethiopia
[2]Assistant Professor , School of Chemical and Biochemical Engineering, Addis Ababa Institute of Technology, 385, Ethiopia
[3]Assistant Professor, Biological and Ecological Engineering, Oregon State of University, USA

Abstract: ***This study identifies three regions of Ethiopia in each continent for algal biomass cultivation considering both sunlight and local climatic conditions. The meteorological data, sunlight, and air temperature information for the identified potential site is combined to estimate annual biomass production, lipid production and carbon mitigation potential. The biomass and lipid productivity in the Ethiopian condition was found to be 93 g/m^2/day and 115,200 l/ha/year, respectively. Among the selected three sites Bahir Dar is best possible for microalgae biomass production (94 g/m^2/day) and oil productivity (33 ml/m^2/day), and has an optimum temperature for microalgae growth. The estimates obtained from the study confirm its realistic potential and will serve the biofuel industry to achieve this target and reduce the losses occurring in the large-scale open pond cultivation system. This study provides a baseline data for theoretical best possible estimates of open pond microalgae production systems in the Ethiopian context. This study will support policy makers in the energy sector to make well-versed decisions to promote a cost effective and environmentally friendly non-edible oil plantation for biofuel production. Finally, it will support the Ethiopian government in its Energy and Food Security policy to promote the use of indigenous and renewable sources for transportation fuels and income generation.***

Keywords: Biomass productivity, lipid productivity, Microalgae, Carbon dioxide fixation, solar radiation

1. Introduction

Demand for energy is increasing every day due to the rapid growth of population and urbanization [1]. According to International Energy Agency (IEA) [2] data from 1990 to 2008, the average energy use per person increased 10% while world population increased 27%. About 80% of this energy demand is delivered from fossil fuels with the consequence of an increase of greenhouse gas emissions in the atmosphere that provokes serious climate changes from global warming. The world today is heavily dependent on fossil fuels. The global increase in carbon dioxide concentration is due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture [3].

Ethiopia’s demand for electricity and petroleum fuels will grow at 11.6 per cent and 9.3 per cent per year, respectively. The demand growth will have serious economic, social and environmental implications and repercussions (the depletion of forest resources will have adverse impacts on fuel supply, soil and water) [4].

Ethiopia belongs to the non-oil exporting less developed countries (LED) of Africa. Ethiopia imports all of its petroleum products and the demand for petroleum fuel is rising rapidly due to the growing economy of about 10% GDP growth and infrastructure development. In the second quarter of 2007/08, petroleum imports exceeded exports earnings by 30%. With the recent trends and volatility of oil prices, the country has been forced to develop a biofuels strategy to mitigate the impacts of imported oil on its economy. The strategy encourages the diversification of energy supplies in the transport sector; therefore, biofuel offers significant opportunities for Ethiopia [4].

All microalgae as renewable source energy for biofuel production primarily comprise of the following, in varying proportions: proteins, carbohydrates, fats and nucleic acids. While the percentages vary with the type of microalgae, there are microalgae types that are comprised up to 40% (20%-80%) of their overall mass by fatty acids [5], and it has higher growth rates and the capability to accumulate higher amounts of lipids [6, 7, 8, 9, 10] than conventional oil crops those are not more than 5% of dry weight [11] and therefore the oil yield per hectare obtained from microalgae can greatly exceed the yield over the next best oil producing crop, oil palms.

Algae can grow in a wide variety of conditions from freshwater to extreme salinity [12, 13]. They are more efficient converters of solar energy than terrestrial plants and take carbon dioxide out of the atmosphere as they grow [14]. Algae is the most optimum organisms for sequestration of CO_2 because of their ability to fix carbon by photosynthesis. The cultivation of algae has been suggested for carbon capture because of its ability to fix CO_2 into biomass and thereby to produce carbon neutral fuels. The prospects of CO_2 mitigation by microalgae is inhibited because of the lack of viable technologies at large scale [15]. The preference towards microalgae is due largely to its less complex structure, fast growth rate and for high oil content.

There are approximately 8,000 species of green microalgae estimated to be in existence. They use starch as their primary storage component. However, nitrogen deficiency promotes the accumulation of lipids in certain species. Green microalgae are the evolutionary progenitors of higher plants and, as such, they have received more attention than other groups [16]. Common microalgae found in Ethiopia: Oedogonium Sp, Botryococcus braunii, Scenedesmus Sp., Chlorella vulgaris, Chroococcus, Synedra, and

Haematococcus Pluvialis, etc. Some these algae strains may contain up to 75 percent lipids making them very suitable for the production of liquid fuels [6, 7].

Microalgae can grow in non-arable land or in dirty water, and when it does flourish, its potential oil yield per hectare is unmatched by any other terrestrial feedstock [12, 17]. All green microalgae are photosynthetic, which means that they get all of their organic carbon (energy) from photosynthesis. Microalgae use energy from the sun to combine water with CO_2 to create biomass [14]. Because microalgae can grow under severe conditions-extremes of temperature, pH and salinity, microalgae-growing facilities can be built on arid coastal land unsuitable for conventional agriculture. Green microalgae are generally fast growing and muscular [7]. The cultivation of algae has been suggested for carbon capture because of its ability to fix CO_2 into biomass and thereby to produce carbon neutral fuels. The prospects of CO_2 mitigation by microalgae is inhibited because of the lack of viable technologies at large scale [15].

Mirage presents one of the most exciting possibilities as a future solution to our energy problems, especially that of transportation fuel. There are several different studies conducted on the theoretical photosynthesis efficiency [18, 19, 20], but they have not been applied specifically to algal photosynthesis on specific Ethiopian climate conditions. Algal productivity based on small-scale experiments were also estimated and reported in different literature [8, 16]. Maximum efficiency and annual algae biomass production yield were calculated based on numerous assumptions without addressing lowest possible yield [21].

Biofuel production from algae has the potential to improve food security, and incomes for Ethiopian families. Crops not used for food can also be considered for biofuel production. Algae has been shown to be very promising as a biofuel, with it’s didn't share the crop land and grow with wastewater and stress handling abilities. New research could even develop ways to use only the non-food feedstocks like microalgae. The need to have renewable energy technologies for Ethiopia is guided by: sustained economic growth and food security, energy security, rising investment pressure and sustainable environment.

The objective of this paper is to determine the biomass and lipid productivity using weather data for three selected locations climates and in order to generate preliminary data under optimum growing conditions of Ethiopian context. Based on the results below and the data from the literature of the biomass and lipid production have been successfully compared within the proposed analysis.

2. Methodology

2.1 Site Selection

The site selected for algae cultivation have to meet the following criteria, such as availability of sunlight throughout the year, favorable climatic conditions, temperature, relative humidity, precipitation and evaporation, land topography and assess to nutrients, carbon sources and water [22].

For the above reasons, microalgae production will not be possible in all regions of the world. The following locations around the world such as the Southern part of Asia, Central Africa, Southern Part of North and South America, South Eastern Australia and Caribbean Islands are suitable for algal mass cultivation [23].

Sites suitable for algal cultivation should have a basic requirement of abundant sunlight. This is undoubtedly an important consideration since insulation is directly linked to biomass yield. About 1367 W/m2 of light energy reaches the outer atmosphere of earth and on average only 240 W/m2 reaches the earth's surface [24]. Annual solar radiation within the world generally varies between 700 and 2500 kWh/m^2. Site suitable for algal cultivation should have a basic requirement of abundant sunlight. This is undoubtedly an important consideration since insulation is directly linked to biomass yield. Tropical countries experiencing more intense sunlight are ideally suited for microalgae cultivation. However, to identify the variation in productivity of each continent, the hypothetical algae biodiesel production facility for this study is considered to be located in eight Ethiopian regional climates as shown in Figure 1.

Three different locations were considered for the microalgae biodiesel facility: Addis Ababa (9^o N, 38.8^o E), Awasa (7.1^o N, 38.5^o E) and Bahir Dar (11.6^o N, 37.4^o E). The hypothetical large-scale open pond algae production facility is considered to be located in different cities of Ethiopia. The sites are assumed to be adjacent to fossil fuel generation plant for access to the CO_2 in flue gas.

The sites selected for the study are based on availability of adequate sunlight, optimum air temperature, abundant rainfall, number of the population, and proximity to industrial area. Annual average solar radiation in Ethiopia is 5.26 kWh/m^2 and the selected sites having annual average horizontal solar radiation greater than 5.0 kWh/m^2 except Addis Ababa (4.99 kWh/m^2), and temperature greater than 16°C are selected for this study. The meteorological data such as solar radiation intensity and ambient temperature of potential sites are obtained from NASA maps/RETscreen software [25].

Figure 1: Map Showing the Selected Sites

2.2 Sunlight Data

Monthly average hourly global radiations for the selected locations were obtained from RETScreen database. The minimum and maximum intensities of solar radiation for Addis Ababa and Bahir Dar were 3.73 and 6.69 kWh/m^2 /day, respectively.

2.3 Weather Data

Monthly average hourly air temperatures for the selected locations were obtained from RETScreen database. The annual average air temperature in Addis Ababa, Awassa and Bahir Dar were 16.2, 17.6 and 18.8 °C, respectively.

2.4 Microalgae biomass production

$$MB_{production} = \frac{\eta_{Transimission} X\, \eta_{Capture} X\, S_I}{E_{microalgae}} \quad (1)$$

where $MB_{production}$ is microalgae productivity in g/m^2/day, $\eta_{transmission}$ is the efficiency of light transmission to microalgae, $\eta_{capture}$ is the efficiency of conversion of incident sunlight to biomass in microalgae, S_I is the solar Irradiance falling on a horizontal surface (kWh/m^2/day), and $E_{microalgae}$ is Energy stored in the biomass (MJ/kg).

2.5 Microalgae lipid production

$$ML_{production} = \frac{f_L X\, MB_{Production}}{\rho_L} \quad (2)$$

where $ML_{production}$ is the lipid productivity from microalgae (ml/m^2*day), f_L is the microalgae Lipid fraction usable for biodiesel, $MB_{production}$ is the microalgae productivity in g/m^2/day, and ρ_L is the density of lipids usable for conversion to biodiesel (kg/L).

2.5.1 Energy stored in biomass

The three primary compositions of microalgae are Lipids, Carbohydrates and Proteins. Oil content in microalgae ranges from 20% to 80% by weight of dry biomass [6]. The amount of microalgal biomass produced per unit of capture energy is called the higher heating value or heat of combustion. Depending on the percentage composition of these fractions, energy stored in the biomass can be determined. The heating value of microalgae was estimated according to the assumed chemical composition with 30% lipid, 35% carbohydrate, 35% protein. The higher heating value (HHV) of microalgal biomass 36.6 MJ/kg [26]. The net calorific value or lower heating value of the major composition of microalgae are summarized in Table 1 [27]. The higher heating values of various fuels are shown in Table 2.

$$\mathbf{E_{microalgae}} = \mathbf{f_L} \times \mathbf{E_L} + \mathbf{f_P} \times \mathbf{E_P} + \mathbf{f_C} \times \mathbf{E_C} \quad (3)$$

Where $E_{microalgae}$ is the energy stored in the biomass (MJ/kg) (L=lipids; P=proteins; C=carbohydrates), f_L is microalgae lipid fraction usable for biodiesel, f_P is microalgae protein content fraction, and f_C is the microalgae carbohydrate content fraction.

Table 1: Biomass fractions and net calorific values

Fraction Molar mass Lower heating (g/mole) value (MJ/kg)
Protein ($C_{4.43}H_7O_{1.44}N_{1.16}$) 100.1 15.5
Carbohydrate ($C_6H_{12}O_6$) 180 13
Lipid (C40H74O5) 634 38.3

Table 2: Higher heating value of various fuels

Fuel HHV (MJ/kg) Reference
Coal 29.3 [28]
Natural gas 54 [29]
Microalgal biomass 36.6 [26]

2.5.2 Transmission efficiency of sunlight to microalgae

Photon transmission efficiency accounts for losses in light distribution, absorption characteristics, land use and photo synthetically active radiation of sunlight. The solar energy available for photosynthesis is called photo synthetically active radiation which ranges from 400 to 700nm of the entire solar spectrum. The land-use efficiency depends on the availability of the growth system for cultivation throughout the year. The geometry and construction of the open pond should be optimized to reduce the light distribution efficiency. Not all the incident photons will be absorbed by microalgae .The number of photons reaching the micro algal growth system depends on the light absorption coefficient of microalgae.

$$\eta_{transmission} = \eta_{light\ distribution} * \eta_{land\ use} * \alpha * PAR_{component} \quad (4)$$

Where $\eta_{transmission}$ is the efficiency of light transmission to microalgae, $\eta_{light\text{-}distribution}$ is the optical light distribution efficiency, $\eta_{land\text{-}use}$ is land-use efficiency, PARcomponent is photo synthetically active radiation of the sun and α is the light absorption coefficient of microalgae.

2.5.3 Solar energy capture efficiency

The capture efficiency of the open pond growth system depends on the efficiency of photosynthesis, absorption, respiration and photo inhibition characteristics of the microalgal culture. The energy required to fix CO_2 and produce chemical energy via photosynthesis is estimated to be 27% as per the Z-Scheme or light-dependent reactions [30]. Some portion of the captured energy is wasted due to respiration in microalgae during the night. The capture efficiency depends on the algae's ability to utilize the sunlight efficiently without photo inhibition.

$$\eta_{capture} = \eta_{photosynthesis} * \eta_{photo\ utilization} * (1 - r) \quad (5)$$

Where $\eta_{capture}$ is the efficiency of conversion of incident sunlight to biomass in microalgae, $\eta_{photo\text{-}\ synthetic}$ is photosynthetic efficiency, $\eta_{photo\text{-}utilization}$ is the fraction of captured photons utilized by microalgae and r is the fraction of energy consumed by respiration in microalgae.

2.5.4 Photon utilization efficiency – Bush equation

Photon utilization efficiency depends on energy available in sunlight and energy at which saturation occurs. The outdoor large-scale open pond production system exhibits photo inhibition due to the extreme condition of sunlight such as low light, highlight, or high temperature. This sub optimal condition leads to poor utilization of the incident photon. This loss would be much more significant for the outdoor system.

$$\eta_{Photo-utilization} = \frac{I_s}{I_l}\left[\ln\left(\frac{I_l}{I_s}\right) + 1\right] \quad (6)$$

Where I_s is the saturation light photosynthetic photon flux density on microalgae (μmole/m^2/s) −quantum of energy at which microalgal photosynthesis attains saturation, I_1 is an incident light photosynthetic photon flux density incident onmicroalgaee (µmole/m^2/s) quantum of energy available in natural sunlight.

2.6 Assumption

Equations (1) –(6) can be solved to determine the biomass productivity, oil productivity and CO_2 fixation, using the input data of sunlight available at a particular selected site and assuming optimum values for unknown variables. The following optimum values of variables are taken from the literature and few of them are assumed s listed in Table 3.

3. Results

3.1. Variation of solar radiation

The average solar radiation received from Addis Ababa, Awasa and Bahir Dar is around 5.8 kWh/m^2/day except Addis Ababa (4.99 kWh/m^2/day). The maximum and minimum intensity of solar radiation was found to be 5.64 and 3.73 kWh/m^2/day, respectively, for Addis Ababa, 6.41 and 4.83 kWh/m^2/day, respectively, for Awasa and 6.69 and 5.16 kWh/m^2/day, respectively, for Bahir Dar. As the productivity of algae is determined by the available solar radiation levels, is important in assessing the potential of algae growth. All the sites selected for this analysis have high solar insolation, providing an ideal combination for algae open pond cultivation. The variations in solar radiation for the three selected sites are shown in Figure 2.

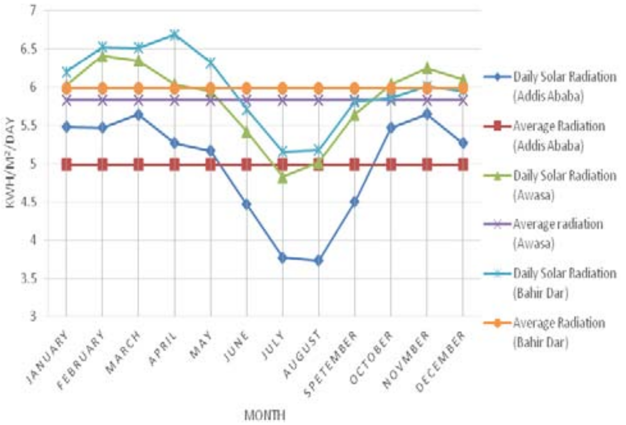

Figure 2: Variation in Solar Insulation across Three Selected Sites

3.2 Variations of air temperature

The temperature required for optimum growth of algae is around 20 to 35 °C [7] for some species like *C. Vulgaris*, but *S. Dimorphus* strain the optimum temperature is around 10 to 40°C [34]. The maximum and minimum annual average air temperatures in Addis Ababa were 17.9 and 15 °C, respectively, 20.37 and 15.73 °C, respectively for Awasa and 21.77 and 16.34 °C, respectively in Bahir Dar. All the sites selected have ideal air temperature for the growth of microalgae and to produce biodiesel. Figure 3 compares the monthly average ambient temperatures for the three selected locations.

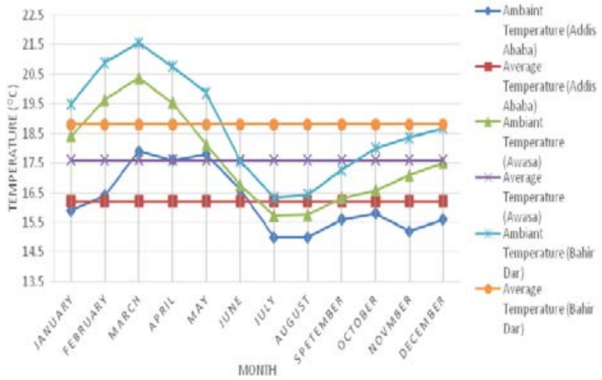

Figure 3: Variation in Air Temperature across Three Selected Sites

Table 3: Optimum Values of Parameters Used in the Calculation

Term Unit Optimum value Reference
$\eta_{light-distribution}$ 0.96 [10]
$\eta_{land-use}$ 0.98 [10]
$\eta_{photo-synthesis}$ 0.27 [31]
$\eta_{photo-utilization}$ 1 Calculated from Equ. 6
E_L kJ/g 38.3 [27]
E_P kJ/g 15.5 [27]
E_C kJ/g 13 [27]
I_s µmole/m^2/s 200 [32]
I_1 µmole/m^2/s 200 [10]
PARcomponent 0.46 [33]
α 1 [10]
r 0.20 [10]
ρ Kg/L 0.864 Assumed

3.3 Biomass and oil yield in selected sites

By knowing the average solar intensity and substituting the values in the above model Equations (1) –(6) [35], the corresponding monthly average biomass productivity and oil productivity can be determined. The biomass and oil yield based on the solar energy available at the site and various efficiency factors closely matches with the other literature data. The daily biomass productivity of the selected sites are summarized in Table 4 giving an average of 78, 91 and 94 g/m^2 /day, for Addis Ababa, Awasa and Bahir Dar, respectively, and Oil productivity of 27, 32 and 33 ml/m^2/day, respectively.

Table 4: Summarized Daily Biomass Productivity for the Selected Sites

Sites	S_I (kWh/m^2/day)	S_I (KJ/m^2/day)	$MB_{production}$ (g/m^2/day)	$ML_{production}$ (ml/m^2/day)
Addis Ababa	4.99	17964	78.23139	27.16368
Awassa	5.83	20988	91.4006	31.73632
Bahir Dar	5.99	21564	93.90902	32.6073

3.4 Variations of biomass productivity

Figure 4 shows the variation of biomass productivity in different months for the selected experimental sites (Addis Ababa, Awasa and Bahir Dar) giving an average biomass productivity of 78, 91 and 94 g/m^2/day, respectively. The maximum biomass productivity of 89 g/m^2/day is possible in the month of November in Addis Ababa, 100 g/m^2/day is possible in the month of February for Awasa and 105 g/m^2/day in the month of April in Bahir Dar.

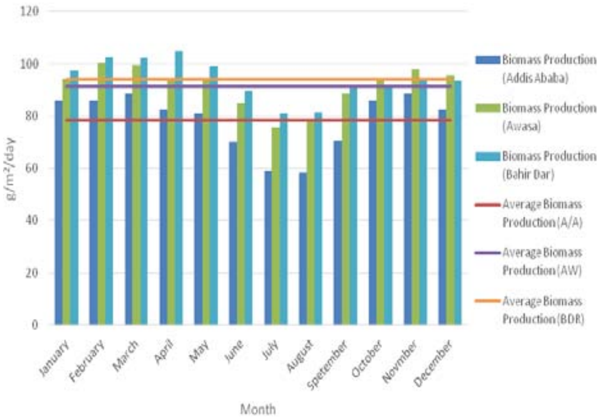

Figure 4: Biomass Productivity in Three Selected Sites

3.5 Variations of oil production

Figure 5 shows the variation of Oil yield in different months for the three selected sites (Addis Ababa, Awasa and Bahir Dar), giving an average oil yield of 27, 31.7 and 32.6 ml/m^2/day, respectively. The maximum oil production of 38 ml/m^2/day is possible in the month of November in Addis Ababa, 35 ml/m^2/day in the month of February for Awasa and 36 ml/m^2/day in the month of April in Bahir Dar.

4. Discussion

On average, 93 g/m^2/day and 32 ml/m^2/day of biomass and oil yield would be possible in the Ethiopian condition. Sudhakar et al. [10] estimated the annual average productivity of 75 g/m^2/day for the India condition. Slightly lower values of 20g/m^2/day have been reported for the small-scale pilot pond system at Israel [36]. A total of 30g/m^2/day productivity of microalgal biomass was measured by the seventh year Aquatic species program project during 1986 and 1987 in the open pond system [16]. The estimated biomass yield for the Ethiopian condition closely matches with other reported literature and experimental data especially on Indian condition. To reduce the dependency on fossil fuels, producing energy from sustainable sources like microalgae can make the country to shift towards a low carbon economy. To produce 13.4 million tonnes of biodiesel as per the national target of 5% blending, 48 million tons of biomass need to be produced. Based on our estimates of the algal biomass yield, only 0.2 million hectares of land is required which is just 0.06% of the Ethiopian land area. The nation has huge potential to meet the biodiesel blend in target. Under Ethiopian conditions, microalgae can be grown abundantly on a large-scale in wastelands for biodiesel production and have the potential to replace a portion of gasoline fuels. Issues such as global warming, CO_2 sequestration and food security can be addressed with algal cultivation. In addition to many environmental benefits, algal biomass offers many economic and energy security benefits. By growing our fuels at home, we reduce the need to import oil, reduce our exposure to disruptions in that supply and thereby generate local employment. However, it was found that the social cost of producing algal biodiesel is higher than rapeseed biodiesel and fossil fuels in the world. Algal biodiesel can replace other fuels with further significant biotechnology development [37].

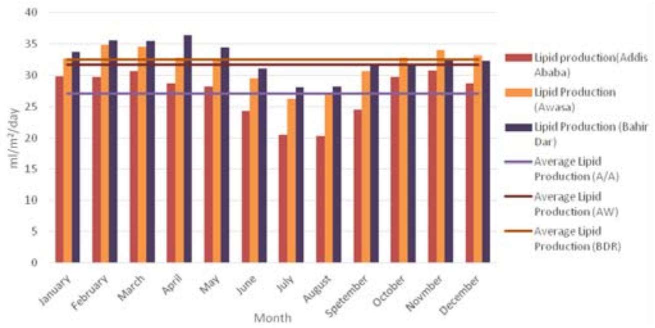

Figure 5: Lipid Productivity in Three Selected Sites

5. Conclusion

The analytical method presented here based on photosynthetic light efficiency can yield a rough estimate of the algae biomass potential in Ethiopia under the ambient condition. The biomass and lipid productivity in the Ethiopian condition was found to be 93 g/m^2/day and 115,200 l/ha/year, respectively. The estimates obtained from the study confirm its realistic potential and will serve the biofuel industry to achieve this target and reduce the losses occurring in the large-scale open pond cultivation system. However, this upper limit of biomass and oil yield can never be improved upon very much in the open pond cultivation system irrespective of the optimum design of the pond and genetic improvements to algal strains. Therefore, the outdoor algae pond should be designed and operated efficiently to maximize algal product yield. It can be concluded from the results that there is a huge potential of algae biodiesel in Ethiopia.

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Author Profile

Abraham M. Asmare received the B.Ed degree in Chemistry from Debub University in 1997-2001 and M.Sc. degrees in Environmental Science from Addis Ababa University in 2004-2006, respectively. By now he is a PhD student at Addis Ababa University in Environmental Engineering and courtesy faculty at Oregon State University. During 2001 to present Lecture at Bahir Dar University.

Berhanu A. Demessie (Dr.–Ing) recived BSc in Chemical Engineering and PhD in Chemical Engineering at Germany. By now he is Head and Ass. Professor at Chemical and BioEngineering School od Addis Ababa University.