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# Turning curse into cure: Potential of water hyacinth for bio-refining - A contextual investigation of Lake Tana

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A B S T R A C T

Water hyacinth (WH, Eichhornia crassipes, 'Emboch' in Ethiopia) is a highly disturbing class of invasive and noxious aquatic plants found worldwide in other water bodies and as such is a prime problem in Lake Tana. One approach to successfully control the rapid invasion of WH is to utilize it as a feedstock to produce high-valued commodities in a biorefinery framework. Preliminary life cycle analysis carried out in the study shows that WH biomass is a competitive feedstock for biorefinery systems with a unit cost at $ 24.40 per ton of dry matter. Based on the annual generation capacity of 0.71 million tons of dry mass in lake Tana and following the standard biorefinery process protocols, the predictions indicate that the economic potential of converting WH biomass into 38.8 billion liters of biomethane alone to be at $ 38.8 million, 74.2 million liters of bioethanol alone at $ 51.9 million, and o.52 million tons organic agro-fertilizer alone at $ 130.5/78.3 million as a partial substitute for Anhydrous Ammonia or Muriate of Potash (MOP) fertilizers. Hence the integrated WH management and utilization as a biorefinery feedstock ranks it among the world's most competitive feedstocks with attractive socio-economic and environmental benefits.

## 1. Introduction

Water hyacinth (WH, Eichhornia crassipes, 'Emboch' in Ethiopia) is originally native of Latin America, especially from the basins of the Amazon and Orinoco rivers. It is a well-known noxious, invasive and problematic waterweed. It is found worldwide in lakes, rivers, and other water bodies causing severe environmental disruption (Simberloff and Rejmanek, 2011). Due to its fast propagation, it is also detrimental to the development of economic activities on the river system (navigation and fishing) (Lowe et al., 2000; Malik, 2007). It is a highly effective invader due to its extremely persistent operating pattern. Once established in an area it can easily outcompete native vegetation, being thus very difficult to control or remove (Walter et al., 2011). It can double its coverage area in around 13 days (for average frequency of 26 cycles per year) (Lareo, 1981).

In Ethiopia, problems with WH have arisen since 2011 in lake Tana (the main tributary of the Blue Nile). The same problem happened in 1956 in lake Koka and in Awash river, with WH being documented as the most destructive plant in 1965 (Kibret, 2018). Lake Tana has a total of 385 km shoreline length. Over 30% of the shoreline suffers from WH infestation (Wassie, 2014), corresponding to more than 50,000 hectares up to 2014 (Sironi, 2018). This disturbance has an enormous effect on the environment and socio-economic systems of inhabitants and the community around a large portion of the Ethiopian lakes and rivers (Dersseh et al., 2019a; Senayit et al., 2004). It represents a dangerous influence on water systems, tourism, water transportation, fisheries, agriculture, power plants, social structures, and living conditions of local society (Dersseh et al., 2019a). The most common links are (1) Cessation of fishing activities and consequently reducing fisherman's income, reducing employment and wealth, increasing poverty, and reducing fishing efficiency (Asmare, 2017). (2) Blockage of waterways, causing flooding, hampering agriculture and recreation (Mitike, 2015; Patel, 2012). (3) Increased evapotranspiration and reduced water quality as large WH mats prevent oxygen from the air to the water surface or decrease oxygen production by other plants and algae (Villamagna and Murphy, 2010). (4)Micro-habitat for a variety of disease vectors and pests like floating mats of WH support organisms that are detrimental to human health like increase of snails serving as a vector for the parasite of Schistosomiasis (Bilharzia) (Borokini and Babalola, 2012), breeding habitat for malaria-causing Anopheles mosquito (Minakawa et al., 2008), and increased incidences of crocodile attacks, and poisonous snakes (Ndimele and Jimoh, 2011; Patel, 2012), and (5) Impact on hydropower - Many large hydropower schemes suffer from WH infestation, causing significant water loss through the evapotran-

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(a) Biological weevils (b) [Manual removal schemes (c) Mechanical removal schemes

**Fig. 1.** WH biological, manual and mechanical removal schemes photos from Jernelov (2017), Sironi (2018), Dechassa and Abate (2020).

spiration system and blocking water passages due to floating WH mats (Shanab et al., 2010). For instance, on the Tana Beles hydropower plant, the WH caused damage to water coolers and generators, prompting the power utility company to switch off generators for maintenance; and causing about 15 Megawatts of electric power loss resulting in power cut in an urban area of Ethiopia (Firehun et al., 2014). Due to the nationally promoted ”Save Tana” project, which fostered manual removal of WH, the infestation decreased to 34,500 hectares in 2015 in the Northern part of the lake (Wassie et al., 2015). It is expected that the infestation might proceed towards the southern end of lake Tana. At that point, it will follow further down the Blue Nile and eventually will reach the Great Ethiopian Renaissance Dam (GERD) (Wassie, 2014). Therefore, removal and control of WH on lake Tana is the top priority and is in the current attention of the Ethiopian government, public and academia.

There are different approaches to expel the plant at present. One is biological control, which introduces other species such as moths, fungi, and weevils (see Fig. 1a) into the ecosystem that must be able to consume the WH plant; and may incredibly influence the aquatic life in the water body (Gichuki et al., 2012; Jernelov, 2017). The main obstacle can be a long time to start such projects because it can take many years to reach enough populations to deal with pests (Villamagna and Murphy, 2010). The second is a chemical control method; it affects the sustainability of water systems by using herbicides and other poisonous synthetic compounds that impact sea-going life (Borokini and Babalola, 2012; Malik, 2007; Villamagna and Murphy, 2010). On the other hand, the third one is physical control (both manual and mechanical removal) most widely utilized technique for WH management; it involves drainage of the water body, manual removal of the weeds (see Fig. 1b), or pulling through nets (Patel, 2012). It needs employing machines like weed harvesters and crusher boats (see Fig. 1c). Due to the above mentioned facts, the utilization of chemical and biological control mechanisms has its related problems but the physical methods seem to be the best choice (Gutiérrez et al., 2000). However, the current practice is to dump the collected weed, which rots, prompting the loss of aesthetics, land, and air pollution (Wassie et al., 2015). Since it is disposed of in a landfill, WH biomass produces a waste gas composed mainly of methane and carbon dioxide; eventually released into the atmosphere due to the lack of a landfill gas control system. Thus, the weed control approach should be associated with its economic exploitation. That could mean not only a reduction in the control costs but also an economic opportunity (Aggarwal et al., 2016). Therefore, such a paradigmatic change could be the key to minimize the environmental problems and control the spread of WH.

Different potential uses for WH have been reported in the literature. Several studies have suggested it as a strong candidate for value added products like biomass feed-stock, biomethane, bioethanol, organic fertilizer, animal feed and further value added productions because of its high productivity (Chin and Goh, 1978; Klass and Ghosh, 1981; Ojeifo et al., 2002). WH has also been reported as a potential candidate for remediation of water bodies (Mata-Alvarez et al., 2000; Ndimele, 2012; Ndimele and Jimoh, 2011).

Many scientists have suggested that biomethane could be produced using WH biomass, a highly controlling strategy to eliminate invasive aquatic plants (Rezania et al., 2015). Chanakya et al. (1993) reported that, due to the low lignin content, the cellulose and hemicelluloses were effectively degraded to produce excellent biomass feedstock for anaerobic digestion (AD) compared with agricultural organic waste, for example, straw. Matsumura (2002) reported that WH biomass chemical composition is averaged to $C_6H_{12}O_{6.8}$ (Gao et al., 2013) and its biogas production efficiency is $62 - 64\%$ and, the pretreatment could improve the efficiency of hydrolysis of cellulose and hemicelluloses, especially regarding break-down of lignin-cellulose and lignin-hemicellulose structures. The chemical content of WH biomass is listed in Table 1 along with the variations as reported in literature (Patel et al., 1993a). It demonstrated enormous contrasts in the composition of WH biomass sourced from different areas, probably brought about by several development stages and development periods at inspection and the impacts of the encompassing ambient environmental condition on the composition of WH biomass.

WH cellulose could be utilized as a carbohydrate to deliver liquid fuels, including ethanol, through hydrolysis and fermentation. This innovation was pioneered in the late 1980s, with ethanol produced from WH biomass by hydrolysis (Kahlon and Kumar, 1987; Ponnusami et al., 2012). Additionally, since WH is a water surface grown plant it does not contend with land assets utilized in sustenance crop development (Bhattacharya et al., 2010). A test was performed to deliver ethanol from WH leaves employing Separate Hydrolysis and Fermentation (SHF). Acidic pretreatment and enzymatic hydrolysis improve productivity to produce more sugars to be aged to ethanol (Sornvoraweat and Kongkiattikajorn, 2011). Another researcher also examined ethanol creation from metal contaminated WH by two techniques. In the principal strategy, saccharification of WH with weakened sulphuric acid ($1\% v/v$ at $110°C$ for $1\ h$) and after that maturation by yeast brought about the production of $55.20\%$ ethanol and $41.66\%$ acetic acid (Mahmood et al., 2010). Hence, the use of WH to produce bioethanol is also a potential approach in controlling the rapid expansion of WH and improving water quality.

Food production requires the administration of fertilizers containing phosphorus, nitrogen, and potassium on agricultural fields to sustain crop yields (Aggarwal et al., 2016; Chen et al., 2010). WH can be utilized both as organic fertilizer on land or as mushroom cultivation media (Chen et al., 2010; Lindsey and Hirt, 1999; Woomer et al., 2000). Phosphorus and inorganic nitrogen present in the roots and C/N ratio make it a consistent substrate for manure or compost (Uka et al., 2007). Drying compost for a couple of days is a significant prerequisite before blended with slag, soil, and some livestock manure (Lindsey and Hirt, 1999; Wolverton and McDonald, 1979). WH compost is a phenomenal natural soil supplement for sandy soil due to its hygroscopic nature, and has high dampness maintenance properties (Aggarwal et al., 2016). Be-

**Table 1**
Chemical compositions of WH biomass from different sources.

| Composition | References | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Polprasert et al. (1980) | Bolenz et al. (1990) | Poddar et al. (1991) | Abdelhamid and Gabr (1991) | Chanakya et al. (1993) | Patel et al. (1993b) | Qian et al. (2011) | Cheng et al. (2013) | Akinwande et al. (2013) | Rathod et al. (2018) |
| Ash | - | 15 | 16.4 | 25.7 | - | 20.2 | 13.4 – 29.2 | 20.8 | 14.85 | 20 |
| C/N ratio | 15.8 | 15 | - | - | - | - | - | - | - | - |
| Calcium | - | - | 2.3 | 0.6 | - | - | - | - | 3.08 | 1.32 |
| Carbon | - | - | - | - | - | - | - | - | - | 38.4 |
| Cellulose | - | 31 | 25.6 | 19.5 | 34 | 17.8 | 17.7 – 27.8 | 27 | - | 24 |
| Crude Fat | - | - | 1.6 | 3.5 | - | - | 1.9 – 2.9 | 0.9 | - | - |
| Crude fibre | - | - | - | 18.9 | - | - | - | - | 22.75 | - |
| Crude Protein | - | - | 16.3 | 20 | - | 11.9 | 8.4 – 20.2 | 21 | 10.01 | - |
| Dry matter (%) | - | 6.2 | - | 9.5 | 9.4 | - | - | - | 9.84 | - |
| Hemicellulose | - | 22 | 18.4 | 33.4 | 18 | 43.4 | 20.0 – 34.4 | 20.3 | - | 30 |
| Hydrogen | - | - | - | - | - | - | - | - | - | 5.85 |
| Lignin | - | 7 | 9.9 | 9.3 | 6.4 | 7.8 | 11.4 – 13 | 10 | - | 16 |
| Magnesium | - | - | - | 0.2 | - | - | - | - | 0.65 | - |
| Nitrogen | 2.9 | - | 2.8 | - | - | - | 1.3 – 3.2 | - | - | 2.9 |
| Organic matter | - | - | 83.6 | 74.3 | 83.5 | - | - | - | - | - |
| Oxygen | - | - | - | - | - | - | - | - | - | 28.1 |
| Phosphorus | 0.5 | - | 0.5 | 0.5 | - | - | 0.3 – 0.6 | - | 0.28 | 0.77 |
| Potassium | - | - | 2.4 | - | - | - | 2.4 – 4.3 | - | 4.13 | 2.78 |
| Sodium | - | - | - | - | - | - | - | - | - | 1.32 |

sides, the slurry from the biogas process contains almost all the nutrients needed for soil conditioning and can be directly employed as fertilizer (Patil et al., 2011). It tends to be used legitimately or can be blended with other organic matters. Composting and treating the soil on an enormous scale can be utilized in the administration of WH (Stoffella and Kahn, 2001). That be a superior solution to food security in the growing population and to address the decline of land-use size for crop production at large (Earnshaw et al., 2012). However,WH roots can absorb lots of heavy metals from polluted water bodies and if it is used for soil conditioning the heavy metals tend to mix with the soil ultimately causing soil pollution. If the soil is used for crop and fruits/vegetables cultivation there is a high chance of bio-accumulation of in human bodies. In this regard, it is to be noted that if in case WH biomass has low-level of heavy metal contamination it may still be good source for biomethane production. But the slurry resulting from production needs to be disposed of appropriately (Guo and Yan, 2017).

Studies have also shown, WH biomass is a decent source of creature feed because of its proved protein and mineral substance accessible to ruminants (Aggarwal et al., 2016). Studies proposed that water content in WH must be decreased from 95% to about 15% or not as much as that to avoid deterioration (Wolverton and McDonald, 1979). Its utilization for creature feed is urged in developing countries to help tackle a portion of the dietary issues (Jafari, 2010). Routine with regards to sustaining non-ruminant creatures on apportions containing WH is pervasive. Fresh WH cooked with rice grain and fish feast and blended with vegetable waste, rice bran, copra cake and salt and copra meal is utilized as feed for pigs, ducks and lake fish in nations like Thailand, Malaysia, China and Philippines (Malik, 2007; Van der Meer and Verdegem, 1996). Other researchers also pointed out the utilization of WH as dairy cattle feed (Kivaisi and Mtila, 1997; Mitra et al., 1997). Akinwande et al. (2013) also, with his study conducted on three water bodies in Nigeria, pointed out that taking in to account the biomass yield, synthetic arrangement, and nutritive capability, WH can be used as a feed for creatures particularly ruminants.

This research focuses primarily on the use of WH in the second-generation bio-refinery framework to produce biomass feedstock, biomethane, biofuels, and other fascinating bio-products, like agricultural fertilizer and animal fodder. Thus, the use of WH biomass to produce value-added products coupled with environmental problems mitigation represents a green development paradigm, taking into account the potential contribution to clean energy and environmental protection. However, the economic feasibility of this paradigm is not yet known in local context, and this article aims to address this inquiry by conducting a preliminary techno-economic analysis.

The contribution of this investigation is two fold. Initially, the study provides basic preliminary techno-economic information on novel integrated paradigms of weed management, clean energy production, and more value-added products. Second, while WH was considered a potential non-food feedstock for biofuel and value-added production, much research has been done on production technologies. Yet, since there is currently no data on economic viability in the local context, this study will address this gap. Because WH is widespread globally and the spread of invaders poses a threat to many aquatic systems, the information from this study could be used as a reference for developing countries facing fast invasion of WH.

## 2. Methodology

### 2.1. Study site

The study site is lake Tana, located in Amhara National Regional State in the North-Western part of Ethiopia, between latitude $10^o58' - 12^o47'$ N and longitude $36^o45' - 38^o14'$ E. Tana is the biggest lake in Ethiopia and has been recorded in the principal 250 lake areas of global importance for biodiversity (Beletew et al., 2016). It holds half of the country's water source for urban, industrial, and agricultural uses, fishing and fishery, tourism, and microclimate mediation (Asmare, 2017). The lake Tana Basin consists of 347 kebeles (lower administrative units) and 21 woredas (districts) in 4 administrative zones (Karlberg et al., 2015; Worku, 2017). Lake Tana, in particular, has 37 islands scattered across the lake, covering magnificent churches and monasteries, some of which date back to the 13th to 14th centuries (Worku, 2017). With an average area of $3,200\ km^2$ and lake, catchment covers an area of $16,500\ km^2$, plays a significant role in the economic and social development of the country (Wassie et al., 2015). For example, the yearly business estimation of fish creation business at lake Tana is about US$1.1 million (Gordon et al., 2007). It is also a sink of Bahir Dar city's urban sewage, industrial and agricultural wastewater. Besides,it is the source of the Blue Nile, which provides up to 60% of the Nile's water and water source to individuals over 123 million individuals in the Nile Basin (Worku, 2017).

Furthermore, despite the efforts of the local community to control the spread of WHs, weeds are still difficult to eradicate from lake Tana. In this regard, according to the 2017 report, the latest weed cover

**Table 2**
Technical analysis of WH harvesting and biomass processing from Lake Tana.

| WH Biomass Growth | | | | |
|---|---|---|---|---|
| $R_{W,in}$ | Percentage water content of WH | 95 % | Parameter | Gunnarsson and Petersen (2007) |
| $A$ | WH coverage area | $5,043 (ha)$ | Parameter | Dessie (2019) |
| $G$ | Annual dry biomass Production | 140 $(tons\ DM/ha\ yr)$ | Parameter | Wang and Calderon (2012) |
| $M_{HT}$ | Total fresh biomass annually | $1.412E+10\ (kg/yr)$ | $= \frac{AG(1000)}{1-R_{w,in}}$ | Eq. (1) |
| $\rho_A$ | WH areal density | $20\ (kg/m^2)$ | Parameter | Wang and Calderon (2012) |
| $t_{yr}$ | Annual working days | $270\ (days/yr)$ | Parameter | |
| $M_D$ | Mas of WH biomass daily harvested | $5.23E+07 (kg/day)$ | $= M_{Ht}/t_{yr}$ | Eq. (2) |
| **Harvest** | | | | |
| $w_{cut}$ | Cut width | $4.8\ (m)$ | Parameter | Dragon (2018) |
| $v_{cut}$ | Cut speed | $133\ (m/min)$ | Parameter | Dragon (2018) |
| $A_H$ | Area harvested hourly | $38,304\ (m^2/hr)$ | $= w_{cut}\ v_{cut}\ (60)$ | Eq. (4) |
| $t_D$ | Hours harvested/day | $8\ (hr)$ | Patrameter | |
| $A_{DH}$ | Daily harvested per harvester | $306,432\ (m^2/day)$ | $= A_H t_D$ | Eq. (5) |
| $M_H$ | Mass plants harvested per harvester | $6,128,640\ (kg/day)$ | $= A_{DH}\rho_A$ | Eq. (6) |
| $N_H$ | Whole number of harvesters required | 9 $(harvesters)$ | $= \frac{M_D}{M_H}$ | Eq. (7)[a] |
| $A_D$ | Total hectares per day harvested | $275.79\ (ha/day)$ | $= \frac{A_{DH} N_M}{10000}$ | Eq. (8) |
| $f_H$ | Re-growth rate to maintain WH mat | 19 $(days)$ | $= \frac{A(10000)\rho_A}{M_D}$ | Eq. (3)[a] |
| $P_H$ | Energy requirement per harvester | $110\ (kW)$ | Parameter | Dragon (2018) |
| **Transportation from lake to storage/lake-shore** | | | | |
| $C_M$ | Connectivity of WH mat | $100\ (pa)$ | Parameter | Petrell et al. (1991) |
| $v_M$ | Speed of pulling WH mat in | $2\ (m/s)$ | Parameter | |
| $\rho$ | Plant volume denity | $167\ (kg/m^3)$ | Parameter | Petrell et al. (1991) |
| $l_M$ | Estimated WH Mat length | $719\ (m)$ | $= C_M(2400)/\rho v_M$ | Eq. (9)[a] |
| $M_M$ | Estimated WH Mat weight | $68,982.04\ (kg)$ | $= l_M w_{cut} \rho_A$ | Eq. (10) |
| $N_M$ | Number of WH mats pulled daily | $758\ (mats/day)$ | $= \frac{M_D}{M_M}$ | Eq. (11)[a] |
| $P_{RB}$ | Row boat energy requirements | $5\ (kW)$ | Parameter | |
| $N_{RB}$ | Number of operators required | 24 | $= \frac{N_M}{t_D(4)}$ | Eq. (12)[a] |
| **Storage** | | | | |
| $M_{W,in}$ | Total water in biomass | $4.97E+07\ (kg/day)$ | $= R_{W,in} M_D$ | Eq. (13) |
| $M_{B,in}$ | Total dry biomass | $2.61E+06\ (kg/day)$ | $= (1-R_{W,in})M_D$ | Eq. (14)[b] |
| $R_{W,rem}$ | Total water removable | 97 % | Parameter[c] | |
| $M_{P,hr}$ | WH Biomass processed per hour | $2.18E+06\ (kg/hr)$ | $= \frac{M_D}{24}$ | Eq. (15)[d] |
| $M_{W,rem}$ | Mass of water removed per hour | $2.01E+06\ (kg/hr)$ | $= \frac{M_{W,in}R_{W,rem}}{24}$ | Eq. (16) |
| $M_{T,out}$ | Total biomass leaving presses | $1.71E+05\ (kg/hr)$ | $= M_{P,hr} - M_{W,rem}$ | Eq. (17) |
| $M_{W,out}$ | Water remaining in biomass | $62,103.61\ (kg/hr)$ | $= \frac{M_{W,in}}{24} - M_{W,rem}$ | Eq. (18) |
| $M_{B,out}$ | Biomass leaving presses | $1.09E+05\ (kg/hr)$ | $= \frac{M_{B,in}}{24}$ | Eq. (19) |
| $R_{W,out}$ | % water leaving presses | 36 $(mass\ \%)$ | $= \frac{M_{W,out}}{M_{T,out}}$ | Eq. (20)[a] |
| $R_{B,out}$ | % biomass leaving presses | 64 $(mass\ \%)$ | $= \frac{M_{B,out}}{M_{T,out}}$ | Eq. (21)[a] |
| $N_P$ | Number of presses required | 6 | Parameter | Hronich et al. (2008)[c] |
| $P_P$ | Energy used by each press | $1,470.88\ (kW)$ | $= \left(13.5\frac{kWh}{ton}\right)\left(\frac{M_{P,hr}}{1000}\right)(1-R_{W,in})$ | Eq. (22)[e] |
| $P_{PT}$ | Total energy used | $8,825.25\ (kW)$ | $= N_P P_P$ | Eq. (23) |

[a] Rounded up to whole number.
[b] 8 $h$ is equivalent to 1 Day.
[c] Manufacturer specification.
[d] Process is continuous for 24 h.
[e] General rule of thumb of the manufacturer: 13.5 $kWh/ton$ fiber per $h$

has been found to be distributed in 21 kebeles stretching across five Woredas (Dera, Fogera, Libo Kemkem, Gonder Zuria, and Dembiya), estimated at 5043 hectares, and covering more than 130 km lakeshore (Dessie, 2019). The significant difference from the previous report is probably due to the rising water level in the lake and its expansion into the principal floodplain during the rainy season, and it considers only the thick and intermediate mats (Dersseh et al., 2019b). Even though under suitable conditions, the WH mass can double itself, and infestation is expected to continue. 5043 hectares of WH infestation area is used for the overall analysis of this study without overestimation.

Therefore, a significant need for paradigm shift is needed to reduce the spread of this species. As mentioned in Section 1, the current trend is to dispose of the collected WH biomass as a landfill. Since there is no exhaust gas recovery system, environmental pollution has its associated problems. For example, according to current estimates, the harvestable potential of the annual WH growth is approximately 14 million tons (see Table 2 : $M_{HT}$). Due to the high cost of harvesting WH, it is essential to identify ways in which the collected biomass can be converted to a value-added product rather than being wasted. Therefore, utilizing the harvested WH biomass as a biorefinery feedstock while considering the technical feasibility and Ethiopia's green development strategy, is expected to be a more effective alternative.

### 2.2. Data sources

Primary and secondary data are used in the study. Basic information is collected through physical site visits including disposal of WH in landfill. On the other hand, secondary information such as WH biomass areal density, WH growth rate, biomethane generation potential, ethanol production size, fertilizer capacity, and all related criteria are collected from websites, literature, and similar project reports.

Market prices are used to estimate the shadow prices of some inputs and outputs. Diesel or gasoline and electricity are valued at their average shadow prices, which are the international market prices of $3(\$/gal)$, $0.15(\$/kWh)$, respectively. The shadow price of biomethane, bioethanol and organic fertilizers (Ammonia, MOP) are estimated at $0.001(\$/liter)$, $0.70(\$/liter)$($2.65 per gallon) of cellulosic bioethanol price and ($500(\$/ton)$, $(300\$/ton)$), respectively, according to a weighted

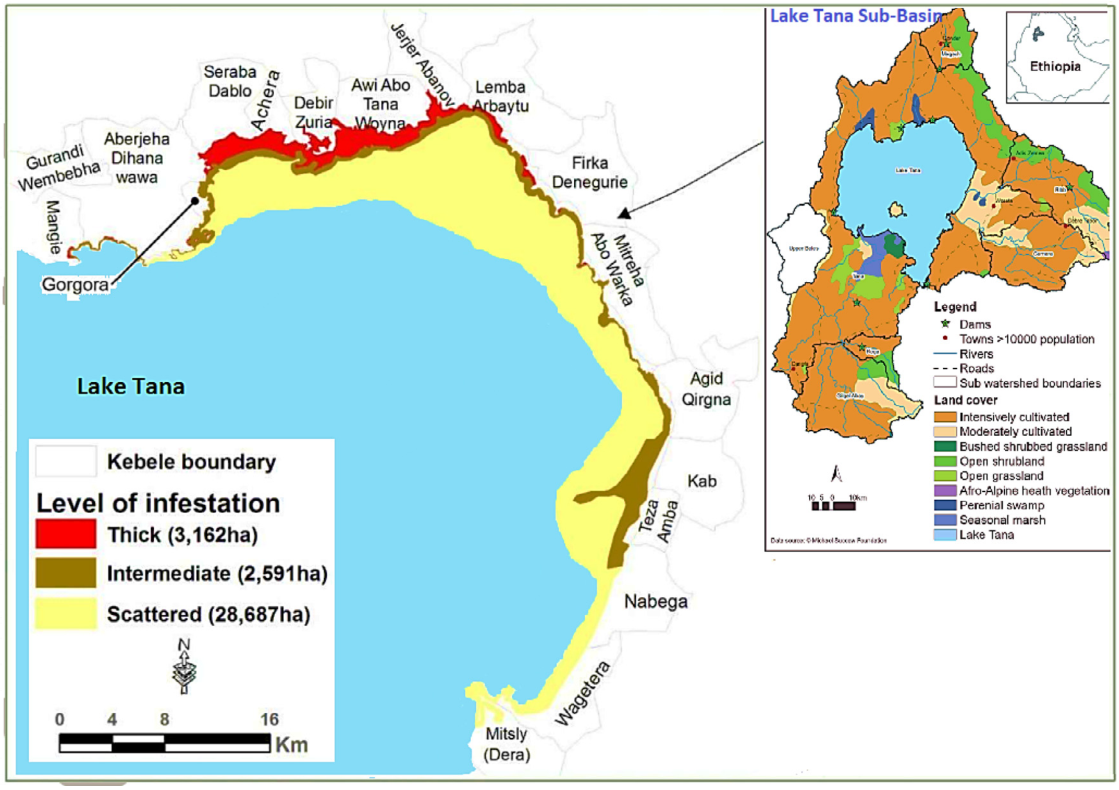



**Fig. 2.** Map of WH infestation status on the shore of lake Tana in May 2015, adapted from Van Oijstaeijen et al. (2020).

average 2020 market price in Ethiopia (Ministry of Agriculture, 2019; GPPe, 2020; GPPg, 2020; Lambert, 2017; Osborne, 2007) (Fig. 2).

### 2.3. Scenario description

To predict the future production economic potential of lake Tana employing integrated WH management and utilization as a biorefinery feedstock with environmental and socio-economic benefits, a technical scheme is developed and outlined in Fig. 3 in terms of two scenarios. The first scenario comprises cost-benefit analysis targeting the harvest and squeezing/pressing WH biomass towards conventional biomass feedstock production (hereafter referred to as the biomass feedstock option). The second scenario involves a preliminary techno-economic prediction of the economic potential of using and transforming the WH biomass in a variety of biorefinery technologies. These include the potential transformation of WH biomass to biogas and subsequently into biomethane production (hereafter referred to as the biomethane option), its potential for bioethanol production (hereafter referred to as bioethanol option), and also its potential for compost production (hereafter referred to as organic fertilizer option). The remaining steps in the refinery are considered to be similar to alternative schemes employing appropriate process and production protocol to produce industrial-grade biomethane (Wang and Calderon, 2012), bioethanol (Wang et al., 2019), and organic fertilizer (Montoya et al., 2013) from WH or other biomass sources.

In addition, many assumptions had to be made considering the paucity of information related to several cost parameters. For example, to reduce logistic costs and ensure sustainable production, the WH biomass processing plant is expected to be centrally located near the lake's shores. The subsidized government grants and tax exemptions are not included as income for collecting and removing the weed. A sustainable biomass supply with a nine-month processing time and three months of maintenance is required in a year (a total of 270 working days per year).

Furthermore, the annual growth rate of WH varies between 8 and 442 tons of dry matter per hectare per year, depending upon location and conditions (Gunnarsson and Petersen, 2007; Hronich et al., 2008; Lareo and Bressani, 1982; Reddy and Sutton, 1984). This study assumes that the yearly production of WH biomass is no more than 140 tons of DM/ha and yr (Abdelhamid and Gabr, 1991; Wang and Calderon, 2012), with an average areal growth density of 20 $kg/m^2$ (Wang and Calderon, 2012). That allows for approximately 0.052 million tons of fresh (wet) WH plants to be collected daily ($M_D$), as calculated by Eqs. (1) and (2) under Table 1. The average water content of fresh WH is assumed to be 95% ($R_{w,in}$) (Gunnarsson and Petersen, 2007), and WH to be harvested per annum ($M_{HT}$) must be lower or equal to the maximum available infested area ($A$) at the source of lake Tana (i.e. $M_{HT} \leq A$). Therefore, the yearly harvested fresh mass prepared is approximately estimated to 14 million tonnes per year (see Table 1: $M_{HT}$).

### 2.4. Biomass feed-stock option

This option considers a mechanical removal method of WH more likened to the saw boat for harvesting, and squeezing or dewatering of wet WH biomass (similar to crushers (squeezer) for the sugar industry). According to the roll presses manufacturer, up to 97 wt% of the water present in fibrous herbaceous materials, such as WHs, can be removed (Fulton, 2013). WH mat's economic harvest is fraught with challenges. The way to the shore ought to stay unhampered, cleared territories ought to be re-grown with plants, and cutting to the whole across region must be planned, so a seamless assortment process results. One convenient option for gathering within these constraints is harvesting through rotation within boundaries of WH infested shore areas (refer to the yellow color width shown in Fig. 4), close by shoreline neighboring 21 kebeles, in 6 weredas.

Note that territory for harvesting would be chosen generally as associated with the focal point of the lake WH infested shoreline boundaries shown in Fig. 4 and adequately enormous enough so a saw boat could

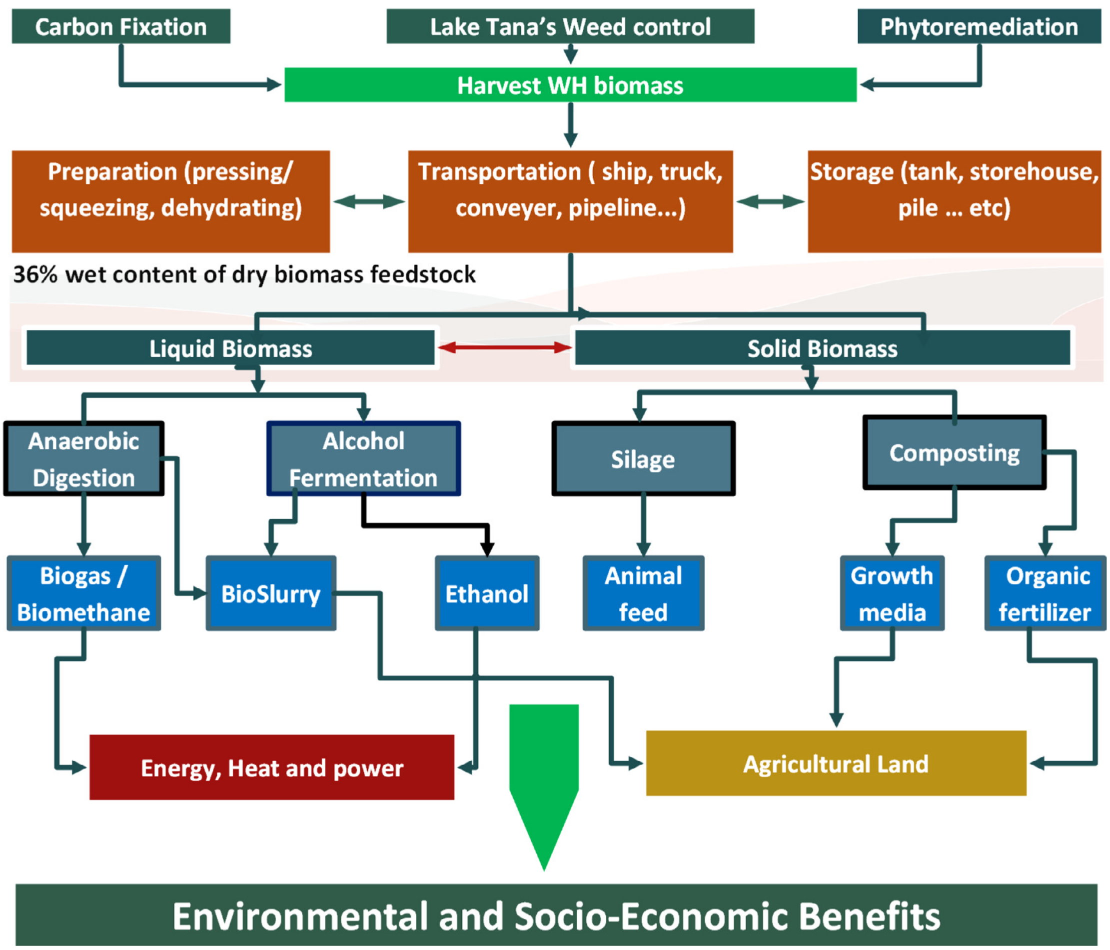



**Fig. 3.** Lake Tana's WH weed control and its potential use structure to turn into environmental and economic benefits.

move unreservedly. At least one cutting zone in the middle of 21 kebeles in 6 weredas would emanate from here. The next zone cutting would be on one side of this cleared territory with the end goal that the opposite side can grow new plants. Along these lines, the cutting zone would move around the center point at a rate that takes into account the most extreme regrowth of the weed biomass and optimizes the productivity of the infested lakeshore boundaries of lake Tana for harvest. Swaths of cut WH plants would be towed to the shore. The primary channel to the central point ought to be wide enough that large boats can pass one another.

During the cutting process, the boat adjusts the number of plants swath to be cut depending on the size of its cutting blade, speed, and the operator's skill to cut bulk plants. Operators of different boats would gather that for collection and lastly them and towing them to shore. When the bundle of WH mats have been brought to shore, they will be fed immediately through a series of roll presses to dewatering. Removing the water content through pressing acts as both pretreatment and decrease storage/transportation costs to remote refineries for further value addition. It is estimated that the plant biomass will have to be squeezed as many as six times to attain this dewatering objective. Due to the high water content of the plant (95 wt%), the compressed biomass will still contain approximately 36% water by weight, as calculated in Table 3.

During pressing, the water removed from the WH biomass is treated and returned to the lake if necessary. The biomass can be moved to further processing to value-added products like biomethane, bioethanol, organic fertilizer, and the like, onshore or remote refineries. In addition, it can be processed with a moisture content of approximately 11%, used for the production of biomass pellets for better storage and transport to distant refineries (Hudakorn and Sritrakul, 2020). Considering the scope of this study the processing cost for this option is not included.

*2.4.1. Biomass feedstock processing design calculations and estimations*

In Tables 2 and 3, a general plant design calculation for processing WH was created to estimate the cost-benefit analysis of harvesting and dehydrating the biomass for various uses. Values taken from the literature, such as annual growth rate, plant density, and mating, etc., are used as input for the calculation. Commercially available harvesters and roll presses have been studied in-depth information on energy needs. To legitimize the estimates, the industry-standard production summary sheet of the chemical process has been revised from discussion papers describing the economies of biorefineries (see Table 3) (Hronich et al., 2008; Ulrich and Vasudevan, 2004).

With 5,043 ha of WH area and yearly growth rate of 140 tons DM/ha per year and with an average areal growth density of 20 $kg/m^2$, lake Tana can roughly provide 0.0523 Million wet tons of WH plants to be harvested every day, as determined by Eqs. (1) and (2).

$$M_{HT} = \frac{AG(1000)}{1 - R_{W,in}} \tag{1}$$

$$M_D = \frac{M_{HT}}{T_{yr}} \tag{2}$$

where $M_{HT}$ is the total fresh biomass mass annually harvested, $A$ is the total infested WH coverage area of lake Tana in hectares, $G$ is the

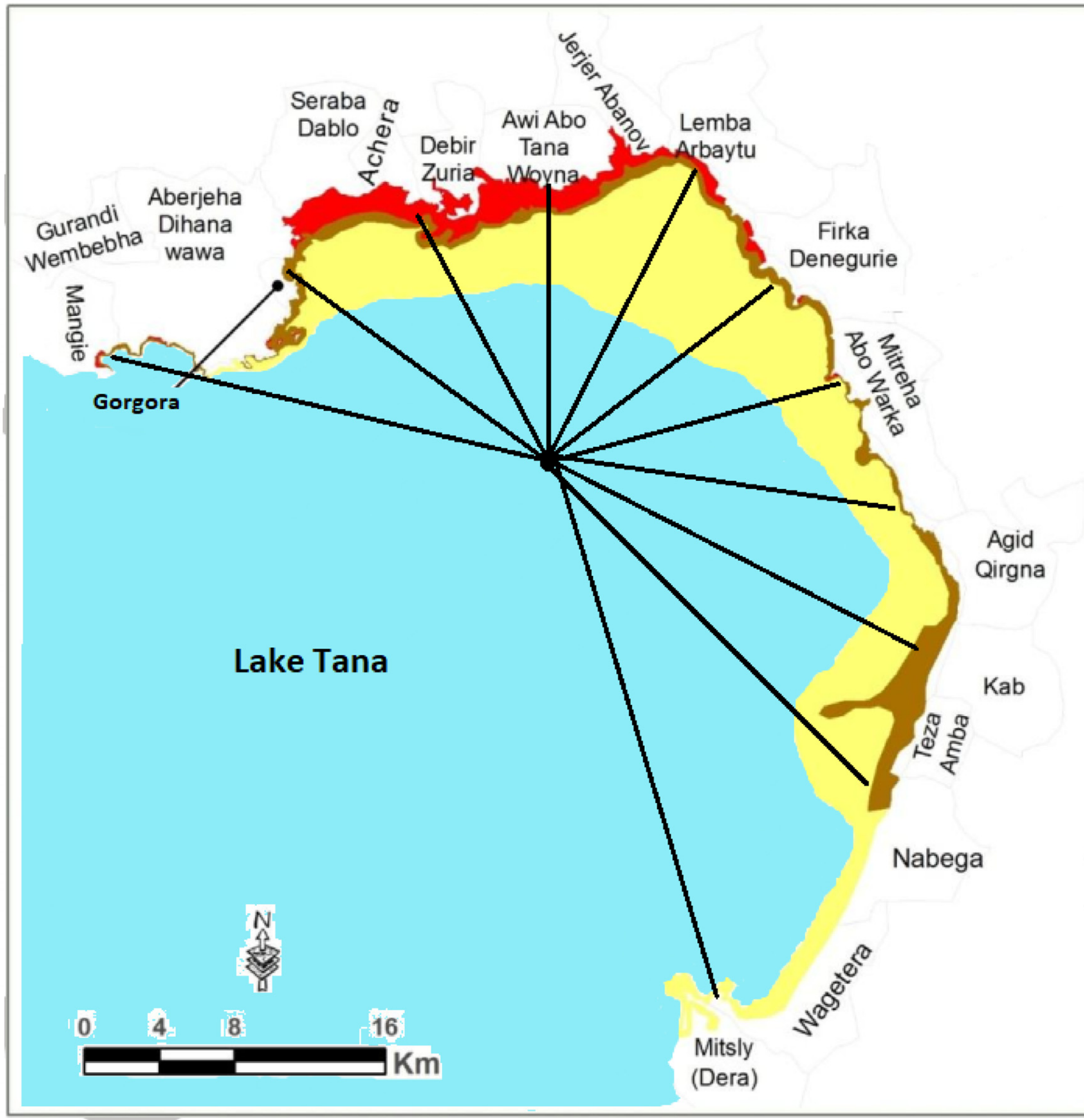



**Fig. 4.** Sketch for lake Tana's WH weed harvesting plan, with lines representing cutting zones with re-rowth void spaces inbetween cut paths.

annual dry biomass production in tons DM/ha per year, $R_{W,in}$ is the percentage water content of fresh WH, $M_D$ is the mass of WH biomass daily harvested, and $T_{yr}$ is the number of harvest days per year. This offers the plants a harvest frequency of 19 days, which is enough for regrowth (Lareo and Bressani, 1982; Penfound and Earle, 1948). The harvest frequency is calculated by Eq. (3).

$$f_H = \frac{A(10000)\rho_A}{M_D} \tag{3}$$

where $\rho_A$ is the areal density in $kg/m^2$.

The commercially accessible WH harvester (Dragon aquatic weed harvester) 110 kW was utilized within the estimation. Expecting an 8-h working hour and 270 yearly working days, a cut speed of 133 m/min, and an 4.8 m wide swath of WH mats, approximately nine harvesters will be required to maintain the daily harvesting goal, as calculated from Eqs. (4)–(7) and shown Table 2.

$$A_H = w_{cut} v_{cut} 60 \tag{4}$$

$$A_D = A_H T_D \tag{5}$$

$$M_H = \rho_A A_D \tag{6}$$

$$N_H = \frac{M_D}{M_H} \tag{7}$$

where $A_H$ is the area harvested hourly in $m^2/h$, $w_{cut}$ is the cut width in meters, $v_{cut}$ is the cut speed in $m/min$, $A_D$ is the daily harvest per harvester in $m^2/day$, $T_D$ is the hours harvested per day, $M_H$ is the mass of WH harvested per harvester in $kg/day$, and $N_H$ is the whole number of harvesters required. The total hectares harvested per day is:

$$A_D = \frac{A_H N_H}{10000} \tag{8}$$

It is recommended to prohibit cutting the lower number of two digits to maintain the WH growth rate, i.e. $A_D$ should be greater than $M_D$ (Hronich et al., 2008). Furthermore, Eqs. (9)–(12) show that 24 simple boats will be required to drag the mats to shore.

$$l_M = \frac{c_M(2400)}{v_m \rho} \tag{9}$$

$$M_M = l_M w_{cut} \rho_A \tag{10}$$

$$N_M = \frac{M_D}{M_M} \tag{11}$$

**Table 3**
Cost benefit analysis of WH harvesting and biomass processing from lake Tana.

| | | | | |
|---|---|---|---|---|
| **Capital** | | | | |
| $C_E$ | Equipment cost | $1.56E+07$ $(US\$)$ | Parameter | see Table 4 |
| $C_S$ | Site | $4.85E+07$ $(US\$)$ | $3.1_C E$ | |
| $C_{fx}$ | Fixed capital costs | $5.03E+07$ $(US\$)$ | $= C_S + C_E$ | |
| $C_W$ | Working capital | $5.03E+06$ $(US\$)$ | $= 0.1C_{fx}$ | Ulrich and Vasudevan (2004) |
| $C_T$ | Total capital costs | $5.53E+07$ $(US\$)$ | $= C_W + C_{fx}$ | |
| **Man-powers** | | | | |
| $MH_H$ | Manpower for Harvesting | 72 $(Man-hrs/day)$ | $= t_D N_H$ | |
| $MH_T$ | Manpower Transporting | 190 $(Man-hrs/day)$ | $= t_D N_{RB}$ | |
| $MH_P$ | Pressing/digestion | 24 $(Man-hrs/day)$ | Parameter | |
| $C_{wege}$ | Wage + benefits | 10 $(US\$/man-hrs)$ | Parameter | |
| $C_{wege,T}$ | Total, per year | $7.71E+05$ $(US\$/yr)$ | $= (MH_H + MH_T + MH_P)C_{wage}T_{yr}$ | |
| $C_{wege,S}$ | Supervisory labor, per year | $7.71E+04$ $(US\$/yr)$ | $= 0.1C_{wage,T}$ | Ulrich and Vasudevan (2004) |
| **Maintenance and operation** | | | | |
| $C_{fuel,H}$ | Fuel for harvesters | $192,462.31$ $(US\$/yr)$ | $= T_{yr}t_D\left[3\left(\frac{\$}{gal}\right)\right] \times \left(\frac{\left[N_H P_H 1000\left(\frac{W}{kW}\right)3600\left(\frac{s}{hr}\right)\right]}{\left[43E06\left(\frac{J}{kg}\right)\right]}\right)\left[\frac{264.172\frac{gal}{m^3}}{737.22\frac{kg}{m^3}}\right]$ | Hronich et al. (2008) |
| $C_{fuel,RB}$ | Transport power required | $23,029.14$ $(US\$/yr)$ | $= T_{yr}t_D\left[3\left(\frac{\$}{gal}\right)\right] \times \left(\frac{\left[N_{RB} P_{RB} 1000\left(\frac{W}{kW}\right)3600\left(\frac{s}{hr}\right)\right]}{\left[43E06\left(\frac{J}{kg}\right)\right]}\right)\left[\frac{264.172\frac{gal}{m^3}}{737.22\frac{kg}{m^3}}\right]$ | Hronich et al. (2008) |
| $C_p$ | Mill press power | $8.58E+06$ $(US\$/yr)$ | $= [N_P P_P]0.15\left(\frac{\$}{kWh}\right)24\left(\frac{hr}{day}\right)T_{yr}$ | Hronich et al. (2008) |
| $C_{MR}$ | Maintenance and repairs | $1.26E+06$ $(US\$/yr)$ | $= 0.1C_E$ | Ulrich and Vasudevan (2004) |
| $C_{OS}$ | Operating suppliers | $1.26E+05$ $(US\$/yr)$ | $= 0.1C_{MR}$ | Ulrich and Vasudevan (2004) |
| $C_O$ | Overhead | $5.26E+05$ $(US\$/yr)$ | $= 0.25(C_{wage,T} + C_{wage,S} + C_{MR})$ | Ulrich and Vasudevan (2004) |
| $C_{LT}$ | Local Taxs | $5.03E+05$ $(US\$/yr)$ | $= 0.01C_{fx}$ | Ulrich and Vasudevan (2004) |
| $C_I$ | Insurance | $1.01E+06$ $(US\$/yr)$ | $= 0.02C_{fx}$ | Ulrich and Vasudevan (2004) |
| $C_{Admin}$ | Administrative costs | $1.32E+05$ $(US\$/yr)$ | $= 0.25C_O$ | Ulrich and Vasudevan (2004) |
| $C_{MO}$ | Total maintenance and operation costs | $1.32E+07$ $(US\$/yr)$ | $= C_{wage,T} + C_{wage,S} + C_{fuel,H} + C_{fuel,RB} + C_P + C_{MR} + C_{OS} + C_O + C_{LT} + C_I + C_{admin}$ | |
| **Depreciation** | | | | |
| $C_D$ | Straight-line depreciation | $2.51E+06$ $(US\$/yr)$ | $= 0.05C_{fx}$ | Ulrich and Vasudevan (2004) |
| $C_{cred}$ | WH removal credit | 0 $(US\$/ha)$ | Parameter | |
| $C_{tot,yr}$ | Total annual cost | $1.57E+07$ $(US\$/yr$ | $= C_{MO} + C_D - (C_{cred}A)$ | Simberloff and Rejmanek (2011) |
| **Biomass production** | | | | |
| $M_{biomass}$ | Dry biomass produced annually | $706,020$ $(tones/yr$ | $= \left[\frac{M_{B,out}}{1000\left(\frac{kg}{tonne}\right)}\right]\left[24\left(\frac{hr}{day}\right)\right]T_{yr}$ | Hronich et al. (2008) |
| $C_{Final}$ | Price per tonne of WH bagasse | 24.40 $(US\$/ton)$ | $= \frac{C_{total,yr}}{M_{biomass}}$ | |

$$N_{RB} = \frac{N_M}{t_D(4)} \tag{12}$$

where $l_M$ is the length of the mat (tangle) in meters, $c_M$ is the connectivity of the mat (network of the tangle) in $Pa$, $v_M$ is the speed of the boats pulling the mats in $m/s$, $\rho$ is the plant density in $kg/m^3$, $M_M$ is the mass of the WH mats in $kg$, $N_M$ is the number of mats pulled per day (is the number of pull points daily), and $N_{RB}$ is the number of operators required for the boats. Key suppositions in these conditions are a period (time) of 10 min to pull a mat to shore, and that one operator is capable of transporting four mats per hour. Situations were additionally researched utilizing the two flatboats and a winch system to transport the floating WH mats to the shoreline for processing; in any case, boats with a tow line have been proven to be very economical due to energy consumption (Hronich et al., 2008).

Once onshore, the WH mats will go through a series of roll presses to remove 95% of the water. This is done both as a pretreatment step, and to reduce the volume for silage. The WH will still contain approximately 36% water by mass after the pressing, as appeared by Eqs. (13)–(21).

$$M_{W,in} = R_{W,in} M_D \tag{13}$$

$$M_{B,in} = (1 - R_{W,in}) M_D \tag{14}$$

$$M_{P,hr} = \frac{M_D}{24} \tag{15}$$

$$M_{W,rem} = \frac{M_{W,in} R_{W,rem}}{24} \tag{16}$$

$$M_{T,out} = P_{p,hr} - M_{W,rem} \tag{17}$$

$$M_{W,out} = \frac{M_{M,in}}{24 - M_{W,rem}} \tag{18}$$

$$M_{B,out} = \frac{M_{B,in}}{24} \tag{19}$$

$$R_{W,out} = \frac{M_{W,out}}{M_{T,out}} \tag{20}$$

$$R_{B,out} = \frac{M_{B,out}}{M_{T,out}} \tag{21}$$

where $M_{W,in}$ is the total amount of water in plants in $kg/day$, $M_{B,in}$ is the total mass of fiber in the same units, $R_{W,in}$ is the total percentage of water removal required, $M_{P,hr}$ is the mass of plant material processed per hour, $M_{W,rem}$ is the desired mass of water removed per hour, $M_{T,out}$ is the total mass of biomass leaving the presses per hour, $M_{W,out}$ is the mass of water remaining in the biomass per hour, $M_{B,out}$ is the mass of fiber in the biomass leaving the presses per hour, $R_{W,out}$ is the percent water in the biomass, and $R_{B,out}$ is the percent of fiber in the biomass. Additionally, it is to be noted that Eq. (15) marks the beginning of a continuous processing is estimated to occur 24 $h$ a day.

The power consumption of each package press is calculated in terms of the manufacturer's estimate in Eq. (22).

$$P_P = \left(13.5\frac{kWh}{ton}\right)\left(\frac{M_{P,hr}}{1000}\right)(1 - R_{W,in}) \tag{22}$$

**Table 4**
Estimated equipment costs.

| Key equipments | Maximum purchased price | 60% price adjustment factor | Quantity | Net price | References |
|---|---|---|---|---|---|
| Big-capacity WH harvester | 300,000 | 180,000 | 9 | 4,320,000 | (Dragon, 2018) |
| Transport boat | 250,000 | 150,000 | 24 | 9,600,000 | (Dragon, 2018) |
| Roll press (Squeezing) machine | 180,000 | 108,000 | 6 | 1,728,000 | (Fulton, 2013) |
| **Total equipment cost** | | | | **15,648,000** | |

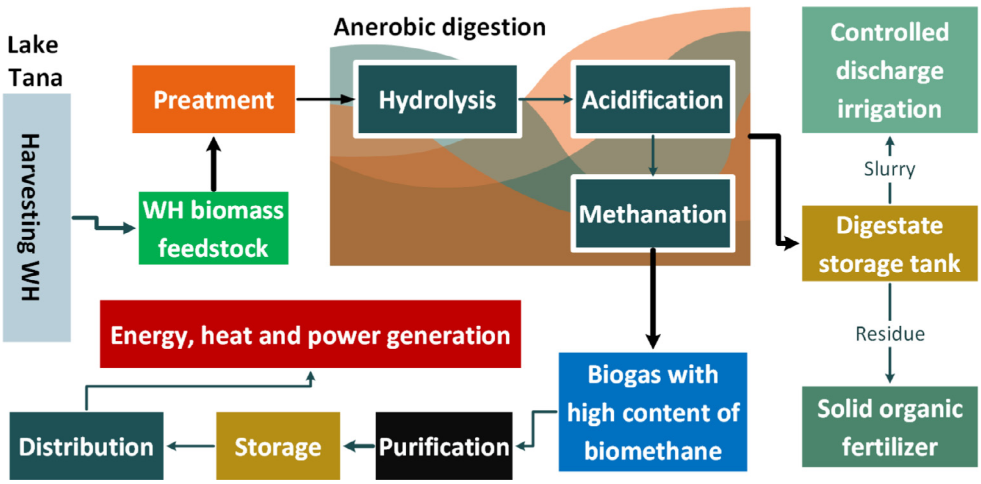



**Fig. 5.** General description of the process for producing biomethane from WH biomass feedstock.

where $P_p$ is the individual power requirement of each press in $kWh$. The number calculated by Eq. (22) is then multiplied by the number of presses to calculate the total press energy consumption ($P_{pT}$), as shown by Eq. (23):

$$P_{pT} = N_p P_p \tag{23}$$

where $N_p$ is the number of roll press required.

*2.4.2. Site and equipment cost estimations*

As the study is a preliminary capital cost estimate, site cost estimates and equipment costs are not based on details or definite evaluation. The site location is on the lakeshore of Lake Tana Gorgora port, free of any land rent cost. This site is selected to erect to process the fresh WH biomass to dry biomass and for distribution. In this regard, considerable key purchased price related to equipment costs ($C_E$= $ 15,648,000) are the total sum of the market prices of harvesting machines, squeezing/pressing machines, and transport boats. All the equipment's are estimated at online purchased price with 60% adjusted local market price as shown in Table 4, the usual Ethiopian local market adjustment price for imported materials. The site costs ($C_S$) are assumed to be some of the indirect costs like site development costs, storage facilities, engineering, buildings, squeezing machines and pipelines installations, and so on. Based on Guo and Yan (2017), these site costs ($C_S$ = $ 48, 508,800) are equivalent to the sum of 300% of the total purchased equipment costs ($C_E$) and 10% of $C_E$. A location factor of 10% of CE was added to calculate the total site costs ($C_S$) in Table 3 (Kumar et al., 2003).

*2.5. Biomethane option*

As an alternative approach to controlling WH proliferation, this option will use the processed WH biomass feedstock to produce biogas and the to biomethane which can be used as fuel for cooking, lighting or for as a heat source for powering a heat engine to provide shaft power/ electricity. General description of the process for producing biomethane from WH biomass feedstock is shown in Fig. 5. Potential biogas production yield from WH, Abdelhamid and Gabr (1991) estimated the annual WH biomass harvest potential per hectare as 140 ton of dry matter. However, WH biomass has a long-term hydraulic retention time due to its sponge-like behavior and floating on the water surface while blocking inlet and outlet pipes during digestion (Chanakya et al., 1993).

In order to overcome the retention time of WH biomass, many studies have developed unique technologies to improve AD in large-scale industrial production. For example, in 1987, Annachhatre and Khanna (1987) invented a two-stage system (acidification phase and methane phase) to acquire high biogas production (440 Liters/kg of total solids) and alkali pretreatment of WH biomass in combination with whole-cell mobilization technology. Chanakya et al. (1992) produced biogas at an average of 250 Liters/kg of total solids, with biomethane content up to 73–83%, and solved the problems of WH biomass floating on the surface of a reactor, and blocking the inlet and outlet pipes using two-phase anaerobic technology with the first anaerobic solid acid phase and the second biofilm-production methane phase.

To increase methane yield, various pretreatment methods have been investigated. These methods can be broadly classified into (1) mechanical processes and, this refers to particle size reduction; (2) chemical processes through the use of dilute acids, alkalis, or organic solvents; (3) physicochemical processes such as steam explosion and hot water; and (4) biological processes, which involve the use of enzymatic means or by microbial consortia Hernández-Beltrán et al. (2019). The effects of different pretreatments methods on the methane yield of different methods are revised and presented in Table 5 with the WH biomass methane yield before and after the treatment.

In biomethane production, high yields are also often obtained by optimizing AD conditions such as C:N ratio, pH, temperature, digestion reactor design and inductions, and inoculums. WH biomass has broad C:N ratios (10-30: 1). The best biomethane production usually reaches around a 15 C:N ratio (Shanmugam and Horan, 2009). The co digestion of WH biomass with other organic waste is regularly used to adjust C:N ratio (Sindhu et al., 2017). Using a different organic waste material source in conjunction with WH biomass, the technology has three purposes: (1) Modify the physical properties of raw materials through pretreatment to have better operational processes during the AD, especially for continuous feeding equipment, (2) Adjusting the C: N ratio to improve methane production, and (3) use different sources for methane production as long as biogas production isn't diminished. For example, municipal solid waste combined with 5% (w/w) WH biomass can hold

**Table 5**
Effects of different pretreatments on methane yield of WH biomass.

| Pretreatment method | Pretreatment condition | Methane yield (Untreated) | Methane yield After treatment | Reaction system | Reference |
|---|---|---|---|---|---|
| | Particle size reduction to 0.001 mm | | Increase 20%(from 50 to 70%) | Digester 0.45 L | Hernández-Beltrán et al. (2019) |
| Mechanical | Particle size reduction to 0.05 mm | - | Increase 16% (from 50 to 66%) | Digester 0.45 L | Hernández-Beltrán et al. (2019) |
| | Particle size reduction to 1.0 mm | | Increase 10%(from 50 to 60%) | Digester 0.45 L | Pellera and Gidarakos (2018) |
| | Particle size reduction to 2.5 mm | | Increase 5%(from 50 to 55%) | Digester 0.45 L | Pellera and Gidarakos (2018) |
| Chemical | Ionic liquids (Disrupt lignin and decrystallize thecellulose) | | Up to 97% | | Hernández-Beltrán and Hernández-Escoto (2018) |
| | organic solvent N-methylmorpholine-N-oxide(NMMO or NMO)(NMMO 85%120 °C; 3 h) | 274 mL/g VS | 304 mL/g VS | Serum bottles 0.125 L | Mancini et al. (2018) |
| | Silfuric acid 5% v/v; 60 min residence time | 58 mL/g VS | 64 mL/g VS | Flask 1 L | Sarto et al. (2019) |
| Biological | Microbial, Citrobacterwerkmanii VKVVG4109 cfu/mL; 4 days | 338 mL/g VS | 373 mL/g VS | Bottle 1 L | Barua et al. (2018) |

**Table 6**
Comparison of the assessment of the previous findings with the present study.

| Input conditions | | Unit | Hronich et al. (2008) | Guo and Yan (2017) | Present study |
|---|---|---|---|---|---|
| $A$ | Water Hyacint coverage area | hectare | 121.41 | 430 | 5043 |
| $G$ | Annual dry biomass Production | ton DM/h.yr | 45 | 100 | 140 |
| $\rho_A$ | WH areal density | kg/m2 | 14 | 20 | 20 |
| tyr | Annual working days | days | 310 | 180 | 270 |
| $w_{cut}$ | Cut width | m | 3.5 | 2.5 | 4.8 |
| $v_{cut}$ | Cut speed | m/min | 45 | 58 | 133 |
| $P_H$ | Energy requirement per harvester | kw | 100 | 127 | 110 |
| $C_E$ | Equipment cost | $ | 192,000 | 1,476,900 | 15,648,000 |
| $C_S$ | site | $ | 1,000,000 | 4,600,000 | 48,508,800 |
| $C_{final}$ | Price per tonne of WH biomass feedstock | $/ton | 40 | 56 | 24.4 |

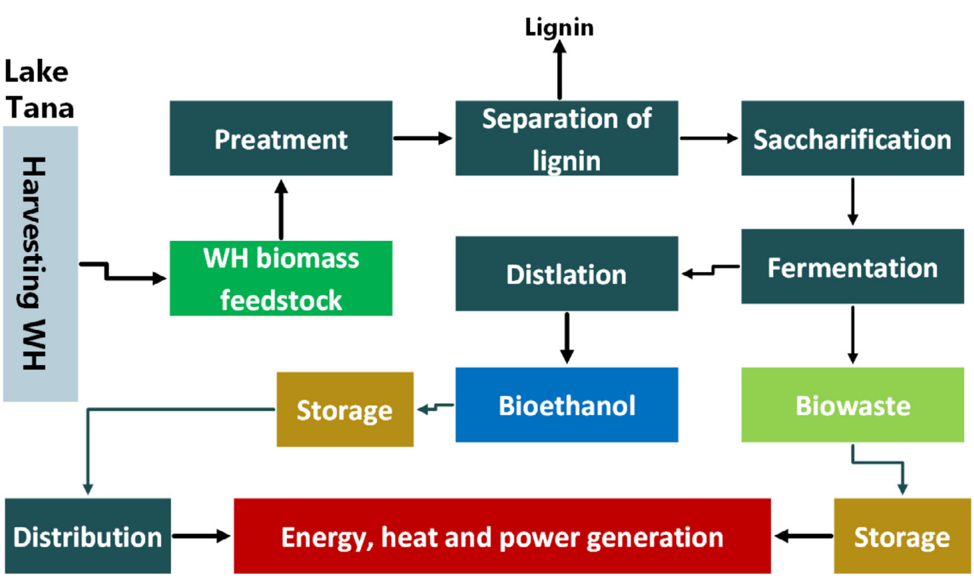



**Fig. 6.** General description of the process for producing bioethanol from WH biomass feedstock.

up to 1.0% (w/w) $Ca(OH)_2$ and reduce the hydraulic retention time by 7 days during the digestion process for each production cycle (70 days). And also increase biogas yield by 33%, methane content by 1.1%, and volatile solid degradation rate by 12% (Wang et al., 2013).

Patel et al. (1993b) obtained and reported WH specific gas yield of 143 liters/kg total solids. More generally, biogas yields from WH have been reported to be between 143 and 291 liters/ kg of total solids with average methane concentrations of 60%, (Gunnarsson and Petersen, 2007). Therefore, the following estimation also considers the minimum biogas yield of 143 liters/kg to not overestimate the yield. This means it is about 143 liters yield of biogas is expected from 1 $kg$ of dried WH biomass. Which then amounts to 85.8 liters biomethane per kg dried biomass.

From Table (3; $M_{Biomass}$), it has been estimated that the yearly dry mass harvestable potential which is equal to 0.71 million tons/yr, with 36% wet content. Based on this, if 143 liters of biogas can be produced from 1 $kg$ of dried WH biomass, 0.71 million tone/yr can produce 64.6 billion liters of biogas per annum (refer to Table 9). This means, 64.6 billion liters of biogas yearly will consume 14 Million tons of fresh WH biomass annually at 95 $wt\%$ content. Or assuming that 60% of pure biomethane in WH feedstock-based biogas production, its biomethane production potential is estimated at 38.76 billion liters per annum.

This shows the potential economic valuation of transforming WH into biomethane is estimated at $38.8 million/yr (with biomethane yield of 85.8 $L/kg$) at 0.001 $\$/liter$ (1 L of biomethane costs 0.001$/liter at 2020 market price). In this regard, the projections made in this study consider the end product has biomethane and its appropriate valuation based on international prices.

### 2.6. Bioethanol option

This represent another option to convert WH biomass to bioethanol which can be used as fuel for cooking, sanitizer production and considered as an alternative to fuel cars, apart from generation of electricity through combustion of the solid waste from fermentation. Pretreatment, saccharification, fermentation, and product recovery are all part of the process of producing bioethanol from lignocellulosic biomass like WH (Sagar and Kumari, 2013). Because fermentable sugars must be released and made available for fermentation, WH biomass must be pretreated, Wang et al. (2019). General description of the process for producing bioethanol from WH biomass feedstock is shown in Fig. 6. In this use scenario, WH converted biomass feedstock discussed in the scenario is considered to be the input feedstock for bioethanol production. While there is no existing production plant that converts WH to bioethanol: this ex-ante study refers to an existing sugarcane-based bioethanol plants in Ethiopia.

Various studies on pre-treatment of WH biomass show that it is a promising, cost-effective, and environmentally friendly technique to deal with WH biomass for biofuel production (Sagar and Kumari, 2013). It demands a relatively high temperature and acid/alkali pre-treatment due to the low sugar content and high lignocellulose substance of WH biomass (Wang et al., 2019). Kumar et al. (2009), attempted ethanol production by pretreating WH biomass with weaker acid, then delivered ethanol through hydrolysis, yielding 0.43 $g/g$ of hemicellulose. Approximately 73 percent of the xylose was converted to ethanol, with ethanol productivity of 0.18 $g/L.h$. Mishima et al. (2008) reported an ethanol production of 0.17 $g/g$ by simultaneous saccharification, and fermentation (SSF); After pretreating powder from the leaves of WH biomass with 1% (w/v), $NaOH$ at room temperature for 12 h and then with 1% (w/v) $H_2O_2$ for another 12 h. A maximum ethanol yield of 0.19 $g/g$ with the productivity of 0.008 $g/L/.h$; could be achieved through SSF when WH biomass pretreated with 10% (v/v) $H_2SO_4$ and over-limed with $Ca(OH)_2$ Isarankura-Na-Ayudhya et al. (2007). Mukhopadhyay and Chatterjee (2010) also reported that, through pre-fermentation hydrolysis and SSF, the highest ethanol yield of 0.21 $g/g$ was produced when WH was biomass pretreated with 0.1 N $H_2SO_4$ and 1% (w/v) $NaOH$, then fermented by Saccharomyces cerevisiae and Pachysolentannophilus. Different WH biomass pretreatment methods for better ethanol yields are reviewed and summarized in the following table.

| Pretreatment method | Reducing sugar | Fermentation mode | Enzyme and Microorganism | Ethanol yield | References |
|---|---|---|---|---|---|
| Using EMIMDP and BMIMA in IL pretreatment | Glucose and total sugars yield of acid pretreatmet were 332 and 584 mg/g of WH. | SHF in flask | S.cerevisiae and cellulase frrom Trichoderma reesei | Ethanol concentration was 0.40 mg/mg glucose | Guragain et al. (2011) |
| 10%, $w/v$ WH with dilute $H_2SO_4$ (2%$v/v$) | The maximum sugar yield was (425.6 mg/g) | SHF in flask | Mixture of S.cerevisiae (MTCC 173) and Z.mobilis (MTCC2428) | Ethanol production was 13.6mg/mL | Das et al. (2016a) |
| Alkaline oxidative (A/O) pretreatment | Final glucose concentration was 16.42 (g/L). | Batch and continuous | S.cerevisiae (KCTC 7928) | Ethanol productivity of continuous fermentation was 0.77 (g/lh), which was 1.57 times higher than that of batch | Ahn et al. (2012) |
| Microwave with 1% dilute $H_2SO_4$ | Highest TRS was 482.8 g/g WH | SSF in flask | P.Stiptis and Pachysolen tannophilus and hydrolysis by Trichodema reesei cellulase | Highest ethanol yields 22 g/g (raw biomass of WH) with 76.3% of the theoretical ethanol yield. Maximum production rate was 0.19 (g/L/h) | Cheng et al. (2014) |
| Three different pretreatment: wet oxidation, phosphoric acid ($H_3PO_4$)-acetone, and ammonia fiber explosion(AFEX) | TRS was for wet oxidation equal to 1.1 g/L and yield of 0.107 (g/g) WH), for phosphoric acid equal to 1.30 g/L and yield of 0.168 (g/g) and for AFEX pretreated WH had 1.4 g/L and a yield of 0.187 (g/g) | SSF in flask | Using S.cerevisiae and Candida shehatae | Highest ethanol titer of 1.52 g/L by AFEX as compared with wet oxidation (1.23 g/L) and phospheri acid-acetone pretreatments (1.31 g/L). | Das et al. (2014) |
| 2.75% $NaOH$ and 1h pretreatment | Sugar consumption were 51.65 and 8% by S.cerevisiae, S.stipitis and co-culture of both respectively | Solid state fermentation in bioreactor | A.niger used for saccharification and S.cerevisiae and P.stipitis used for fermentation | Ethanol produced from S.stipitis and by co-culture of both, with 4.3, 6.2 and 9.8 g/L, respectively | Singh et al. (2016) |
| Pretreatment by 1.5% (v/v) $H_2O_2$ and 3%(w/v) $NaOH$ | Reducing sugars were (223.53 mg/g dry) compared to 48.67 mg/g dry in the untreated sample | SSF and SHF in flask | Enzymatic hydrolysis by cellulase using newly isolated Kluyveromyces marxianu K213 and control S. cerevisiae | Maximum ethanol (7.34 g/L) obtained in SHF using K.marxianu K213 that was 1.78-fold greater than angel yeast S.cerevisiae (4.94 g/L). | Yan et al. (2015) |
| Varying concentrations of $H_2SO_4$ (0.1, 0.5, 1, 1.5 or 2%) at a ratio of 1:8 | 1.96-3.79 g/L was yield of glucose and xylose, 3.79-5.27 g/L of total reducing sugars. | SHF in flask | C. intermedia, P. stipitis, P. tannophilus and S. cerevisiae | Ethanol production by: P. tannophilus (0.043), P. stipitis. (0.037), C. intermedia (0.021), S. cerevisiae (0.015 g/g) | Manivannan and Narendhirakan-nan (2015) |
| 1% $H_2SO_4$ at 100 °C for 30 min 0.5% $NaOH$ at 40 °C for 30 min and microwave-alkaline (150 W microwave acombined with 0.5% $NaOH$ for 0.5 min) | In optimized condition 402.93 mg/g and (197.60 mg/g in hydrolysates, and 205.33 mg bby residue hydrolysis) reducung sugar was produced. | SSF in flask | Using cellulase and S.cerevisiae | The optimized condition was at 38.87 oC in 81.87h when inoculated with 6.11mL yeast and 1.29 g/L bioethanol was produced. | Zhang et al. (2016) |
| Sodium hydroxide with a biomass loading of 10% (w/v), 5% (w/v) concentration of $NaOH$ soaked for 1 h and treatment time of 10 min at 130 °C. | Maximum TRS (0.5672 g/g) was obtained using 9.92 (%w/w) substrate concetrations. | SHF in flask | Cellulase from Trichoderma reesei and xylanase from Termetes versicolor for saccharification and Pichia stipits, Candida shehalae and S. cerevisiae for fermentation | Maximum ethanol 10.44 g/L using Pchia stipitis, followed by 8.24 and 6.76 g/L for C.Shehatae and S.cerevisiae. | Das et al. (2015) |
| Microwave-assisted alkali and organosolve | In optimized condition TRS yield was 12.35 ± 0.09g/L, in flask and bioreactor respectively | SSF in flask and bioreactor | GH5 isolated from C. thermocellum + recommbinant hemicellulase GH43 + S.cerevisiae + C.shehatae | Optimized shake flask and bioreactor SSF yield ethanol titer of 9.78 and 13.7 g/L, respectively. | Das et al. (2016b) |

**Table 7**
Processing cost estimation, revised values.

| Operating costs ($/dry ton biomass) | |
|---|---|
| Manufacturing expenses | |
| **Direct** | |
| Removal credit | |
| Operating labor | $ 1.08 |
| Supervisory and clerical labor | $ 0.11 |
| **Utilities** | |
| Fuel | $ 0.29 |
| Electricity | $ 12.15 |
| Maintenance and repairs | $ 2.22 |
| Operating suppliers | $ 0.22 |
| Operating supplies | $ 0.85 |
| **Indirect** | |
| Overhead, packaging, storage | $ 0.91 |
| Insurance | $ 1.82 |
| **General expenses** | |
| Administrative costs (25% of overhead) | $ 0.21 |
| Depreciation | $ 4.54 |
| **Total cost to produce, per dry ton** | **$ 24.40** |

However, as per Wang et al. (2019), the average bioethanol yield of dry WH biomass feedstock is $0.1289\ g/g$ ($164\ L/ton$). Considering the reported findings, a conservative estimate of $0.1289\ g/g(164\ L/ton,)$ which is lowest among the ones. This implies 0.71 Million tons of dried WH biomass with 36% moisture content [in line with 35.7%], (Hronich et al., 2008; Wang et al., 2019) (calculated under Table 3) can produce 74.2 Million liters of bioethanol annually. Since the water content of fresh WH biomass is 95%, annual production of 74.5 Million liters of bioethanol will consume 14 Million tons of fresh WH annually. That shows the potential economic valuation of transforming WH into bio-ethanol is estimated at $51.9 million at $0.70\$/L$ (that is, estimated at 1 liter of cellulosic bioethanol costs $0.70\$/L$ ($2.65 per gallon) at a weighted average of 2020 at international market price (Osborne, 2007)).

### 2.7. Organic fertilizer option

One-third of the world's population lives on small farms. Most of that developing countries and most of their water bodies have WH weeds, (Wright et al., 2012). Chemical fertilizers are often unavailable or too expensive for local small holder farmers. A large number of nutrients in WH biomass can be a source of fertilizer for small and large scale farmers as organic fertilizer, (Gunnarsson and Petersen, 2007). The use of WH biomass as a source of organic fertilizer helps in local economic growth, agricultural productivity enhancement and food security. Along the way, it controls weeds from infested water bodies (Singh and Kalamdhad, 2012). For example, in Sri Lanka, WH biomass mixed with other organic biomass waste, ash, and soil are sold to farmers (Jafari, 2010).

Phosphorus and inorganic nitrogen present in the roots and C:N ratio (24 : 29) make it a reasonable substrate for manure or compost (Uka et al., 2007). Urea blending is frequently prescribed to accelerate the breaking down procedure Hasan and Chakrabarti (2010). WH compost blended other compost ready from different sorts of livestock excreta,kitchen wastes, crop residues, house sweepings, vegetable wastes, and so forth, has been utilized to improve water holding potential of soils in drought-prone areas Stephan and Selvaraju (2012). In developing countries where mineral soil conditioner is costly and soil quality is poor, it is one of the best options for the issue of controlling WH spread (Ndimele and Jimoh, 2011). Gajalakshmi and Abbasi (2002) researched the effect of the use of compost and vermicompost produced from WH plants, on as far as development and blooming of the angiosperm Crossandra undulaefolia. Results showed that the use of vermicompost prompted noteworthy improvement in the development and blossoming of Crossandra contrasted with the untreated plants. Likewise, the effect of vermicomposting was additionally may be a better process option for wastes and roots of WH with high heavy metal concentrations (Whittle and Dyson, 2002).

To estimate the organic agro-fertilizer potential of WH biomass one need to consider 10% moisture content of WH biomass (Chen et al., 2011); since it is possible to produce (0.71 million tons of WH biomass at 36% moisture content, which is equivalent to 0.522 million tons with 10% $wt$ moisture content. It also expected that during composting the weight will be reduced by up to 50% (Chen et al., 2011). However, the weight reduction also depends on the type of composting (50% for traditional pile composting to very little in bokashi method) (Lew et al., 2021). Conservatively the 50% output has been considered in this study and the annual possible production is 0.261 million ton of organic compost. If the average price per ton for Anhydrous Ammonia is $US\$500$ and the two most common potash fertilizers that increases the crop yield, sulfate of potash (SOP) or muriate of potash (MOP) is $US\$300$ (Ministry of Agriculture, 2019), then the potential economic valuation of transforming WH into organic bio-fertilizer as a substitute for Anhydrous Ammonia and SOP/MOP is estimated at $US\$130.5$ and $US\$78.3$ Million per Annum, respectively.

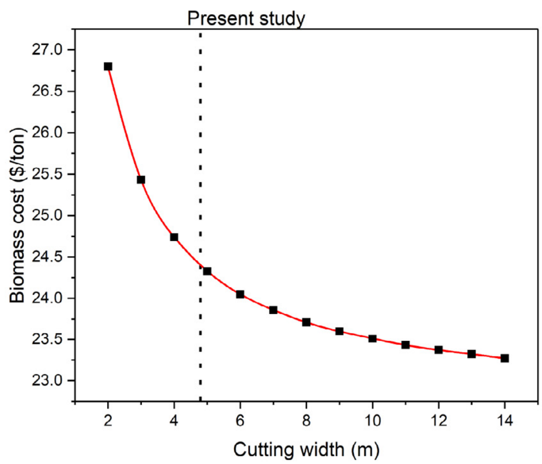
## 3. Result and discussions

As lake Tana has vast ecosystem services, WH infestation has many impacts on human welfare. The knowledge and capacity to manage, control and utilize WH to solve major issues concerning water, energy,and food nexus that are still in the early stages. At present, the knowledge on this technical and economic valuation is insufficient for a clear understanding and a unified opinion on solutions in the local context. To achieve the targets of management, control, and utilization of WH, the mitigation of its potential spread as an aquatic weed, and the conversion of biomass to bio-energy or organic fertilizers or feed are vital for socio-economic and environmental benefits. Furthermore, harvesting the weed will increase the fish catch, recreational activities, and environmental quality. The methodology employed to make projections under different scenarios has been validated by reproducing the results reported by Hronich et al. (2008) and Guo and Yan (2017) for respective operating conditions employed in their studies.

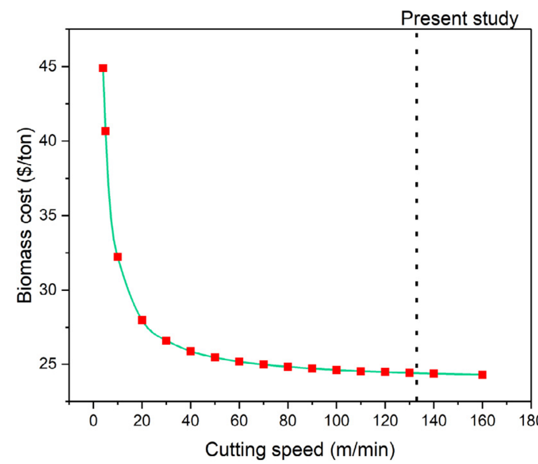
### 3.1. Projections for WH biomass feedstock scenario

Under this scenario, the biomass feed-stock option life cycle cost-benefit analysis (Tables 2 and 3) shows that the total annual harvest and dehydrating cost is $ 10.7 million. This means that about 14 million tons of fresh WH biomass (95% moisture content) or 0.71 million tons of dry (36% moisture content) WH biomass is processed each year (Table 3: $C_{total,yr}$). The price of a ton of production is estimated at $ 24.40. However, snseivity of several input factors affect the final price of a ton of processed biomass (see Fig. 7); the main ones being harvester width (refer Fig. 7a), harvester cut speed (refer Fig. 7b), annual dry biomass production in tons of $DM/ha$ of the WH infested area (refer Fig. 7c), WH areal density in $kg/m^2$ of the infested area (refer Fig. 7d), pressing machine electricity consumption, and transport boat fuel consumption. However, compared to other parameters, boat fuel consumption does not have a significant impact on the final price of dry biomass (Hronich et al., 2008). Accordingly, even if the fuel consumption used in the estimate is incorrect, the final price of WH biomass feed-stock will not be significantly affected. The sensitivity analysis showed that the biomass cos steeply decreases with any of the independent parameters then levels of with negligible incremental reduction.

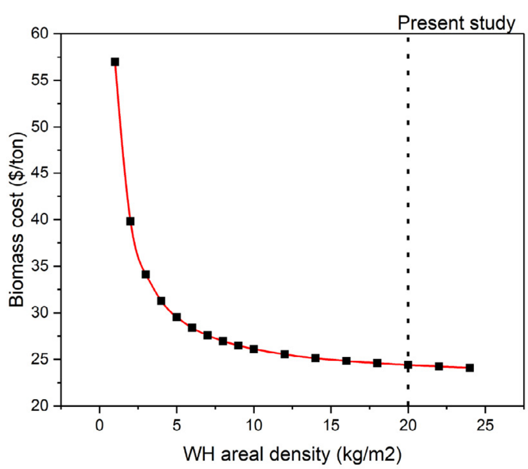
The unit cost of dry biomass ($\$24.40/ton$) is less than nearly half the price detailed by Hronich et al. (2008) ($\$40/ton$) and Guo and Yan (2017) ($\$56/ton$). It can be due to the assumed yearly working days (270 days/yr), annual production (140 tons DM / ha and yr) appraisal, the optimum cutting width and speed at 4.8 m and 133 m / min individually and thick WH mats anticipated in the northern part of the lake; And



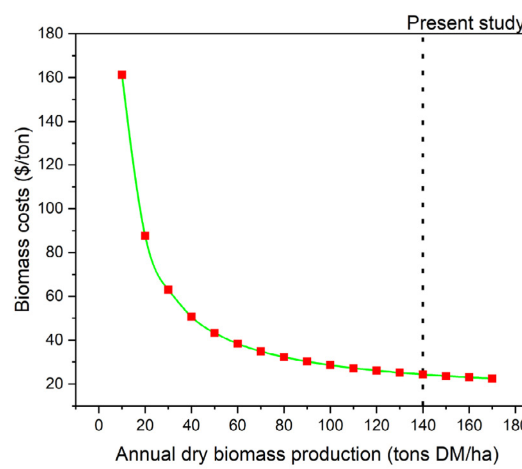

(a) Biomass price per dry ton as a function of harvester cut width in meters, with other input factors kept constant.




(b) Biomass price per dry ton as a function of harvester cut speed in meters per minute, with other input factors kept constant.




(c) Biomass price per dry ton as a function of WH areal density in $kg/m^2$, with other input factors kept constant.




(d) Biomass price per dry ton as a function annual dry biomass production in tons of $DM/ha$, with other input factors kept constant.

**Fig. 7.** Sensitivity of the dominant input factors that effect the final feedstock price per ton.

other input factors are outlined in Table 6 compared to previous studies. Compare to previous estimates by, (Guo and Yan, 2017; Hronich et al., 2008) and (Turhollow, 1994), this unit cost is very competitive in the context of lake Tana. Table 7 summarizes how much each step contributes to the ultimate cost of the WH biomass feed-stock, taking into consideration all of the finer details. The interdependence among the three independent variables is also highlighted in Table 8.

As a result of the forecast for lake Tana WH infestation, government and stakeholders are willing to spend cash on weed control in the future. For example, based on a comprehensive assessment by Van Oijstaeijen et al. (2020), small stakeholders around lake Tana (mostly farmers and fisheries) are willing to raise half a million dollars (proportionate to $US\$109/ha$) a year. This amount can be taken as a weed evacuation credit for ecological compensation. In case this ecological compensation is included within the calculation, the income will reach $US\$17.8$ million yearly (with $US\$24.40/ton$ of dry biomass easily covering the cost of harvesting and dehydration). However, government subsidies for ecological compensations have not yet been quantified and are not included here.

### *3.2. Projections for WH biomass feedstock into biomethane, bioethanol and organic fertilizer scenarios*

Under these scenarios, the discussion will focus on the economic impact of biomethane, bioethanol and organic fertilizers based on the prediction of WH biomass discussed in the Table 9. It provides the economic projections for WH biomass feedstock into biomethane, bioethanol, and organic fertilizer options based on lake Tanas' maximum dry WH biomass feedstock potential studied under the feedstock option (scenario one). It assumed the current international market price of ethanol, biogas, and organic fertilizer includes all the processing costs in the biorefinery process. For example, the proposed 0.70($/liter) or ($2.65 per gallon) cellulosic bioethanol market price considers the total cost of production in the biorefinery. The potential economic valuation of converting WH biomass to biometane, bioethanol and organic bio-fertilizers (as partial substitutes for Anhydrous Ammonia/MOP) is estimated at $ 38.8, $51.9, and ($ 13.5 /$ 78.3) million per year, respectively.

The outcome additionally shows that contrasted with these scenarios, the current physical removal system, and disposal as a landfill ap-

**Table 8**
Variation of biomass cost with different independent parameters.

| Cutting width (m) | Cutting speed(m/min) | WH areal density (kg/m2) | Biomass cost ($/ton) |
|---|---|---|---|
| 1 | 133 | 20 | 30.91 |
| 2 | 133 | 20 | 26.8 |
| 3 | 133 | 20 | 25.43 |
| 4 | 133 | 20 | 24.74 |
| 5 | 133 | 20 | 24.33 |
| 6 | 133 | 20 | 24.05 |
| 7 | 133 | 20 | 23.86 |
| 8 | 133 | 20 | 23.71 |
| 9 | 133 | 20 | 23.6 |
| 10 | 133 | 20 | 23.51 |
| 1 | 2 | 20 | 230.66 |
| 2 | 4 | 20 | 75.98 |
| 3 | 10 | 20 | 37.93 |
| 4 | 20 | 20 | 29.05 |
| 5 | 30 | 20 | 26.42 |
| 6 | 40 | 20 | 25.24 |
| 7 | 60 | 20 | 24.39 |
| 8 | 80 | 20 | 23.96 |
| 9 | 120 | 20 | 23.63 |
| 10 | 140 | 20 | 23.49 |
| 1 | 2 | 4 | 1062.66 |
| 2 | 4 | 8 | 155.92 |
| 3 | 10 | 12 | 48.1 |
| 4 | 20 | 16 | 30.64 |
| 5 | 30 | 20 | 26.42 |
| 6 | 40 | 24 | 24.81 |
| 7 | 60 | 28 | 23.9 |
| 8 | 80 | 30 | 23.54 |
| 9 | 120 | 32 | 23.28 |
| 10 | 140 | 36 | 23.13 |

**Table 9**
Estimation of Biomethane, Ethanol and compost production from 0.71 million tons/yr of WH biomass feedstock with 36% wet content.

| Item | Yield | Price | Yearly Production | Annual revenue |
|---|---|---|---|---|
| Biomethane | $85,800\ (L/ton)$ | $0.001\ (\$/L)$ | $3.88E+10\ (L/yr)$ | $3.88E+07\ (\$/yr)$ |
| Bioethanol | $164.2\ (L/ton)$ | $0.70\ (\$/L)$ | $7.42E+07\ (L/yr)$ | $5.19E+07\ (\$/yr)$ |
| Organi fertilizer | Amonia | $500\ (\$/ton)$ | $2.61E+05\ (tons/yr)$ | $13.05E+07\ (\$/yr)$ |
| | MOP | $300\ (\$/ton)$ | $2.61E+05\ (tons/yr)$ | $7.83E+07\ (\$/yr)$ |

proach of controlling WH proliferation is not a good social investment, as it has two significant shortcomings. First, the biomass of WH isn't utilized but discarded as waste. Second, the outflow of landfill gas is disregarded due to lack of a gas collection framework and in this manner expands GHG stock in the climate. We cannot conclude on the economic legitimacy of the current system, compared to ”do nothing”, because the losses incurred by the WH invasion are not estimated. However, waste gas emissions need to be addressed.

Preliminary life cycle analysis carried out in this study shows that WH biomass is a competitive feedstock for biorefinery systems with a unit cost at $ 24.40 per ton of dry matter. Based on the annual generation capacity of 0.71 million tons of dry mass in lake Tana and following the standard biorefinery process protocols, the predictions indicate that the economic potential of converting WH biomass into 38.8 billion litters of biomethane alone to be at $ 38.8 million, 74.2 million litters of bioethanol alone at $ 51.9 million, and 0.52 million tons of organic agro-fertilizer alone at $ 130.5/78.3 million as a partial substitute for Anhydrous Ammonia or Muriate of Potash (MOP) fertilizers.

Ethiopia is a landlocked and oil-free country and is highly dependent on imported oil products. It is estimated that the country gets more than 1 million metric tons of oil from neighboring Sudan to the port of Djibouti every year, with the estimated cost at $ 1.12 billion each year (Tekalign, 2019). Since 2009, Ethiopia has mixed 59.6 million liters of ethanol with petroleum by adding 5% and then increased the ethanol content to 10%. To this day, Oil Libya, Nile, and National Oil Company (NOC) are blending ethanol supplied by Fincha and Metehara Sugar Factories, (Gebreyohannes, 2013). To this end, the capacity of 74.2 million liters of bioethanol from the WH biomass of lake Tana could help the Ethiopian government. By 2030, it could support the country's plan to save $ 19.2 million to $ 63.2 million in foreign exchange, (Gebreegziabher et al., 2014). Besides, since this biomass source is sustainably controlled, it is possible to predict that the benefit might last long.

Although the government has taken the initiative to invest in local factories by building four fertilizer factories in Oromia, Amhara, Tigray, and Southern regional states, Ethiopia is also dependent on imported fertilizer products, (TAK-IRDI, 2016). According to an estimate, Ethiopia's growing demand for fertilizers is 1.2 to 1.5 million metric tons per year and as a result, the country needs $ 550 million annually (Ministry of Agriculture, 2019). With 0.261 million metric tons of organic fertilizer per year (refer Table 9), lake Tana can produce more than 30 percent of the demand from WH biomass and hence the country can save more than $ 130.5–78.3 million from the current chronic foreign exchange deficit. This forecast is based on the potential for WH-based organic agro-fertilizer, which can be expected to vary over time due to production capacity and cost related parameters, but is still important for the Ethiopian economy. Therefore, converting WH weeds into organic bio-fertilizers is more profitable in all respects than biomethane and bioethanol alternatives. While the economy is not a major driver of a paradigm shift, it is committed to greater commitment. It can make a significant contribution to Ethiopia's political vision and economic reality.

Furthermore, the coupled action of WH management and utilization as a biorefinery feedstock for the production of biomethane, bioethanol, and organic fertilizers primarily helps to reduce GHG emissions and protect clean water from pollution. It also reduces the pressure on bio-oil crops, provides socio-economic rewards by creating job opportunities for weed removal and for the biorefinery system. The harvesting is a source of income for the local people, it increases fishing volume, increases recreational activities, and the quality of the environment. If the above economic projection proposals are accepted and implemented, it will reduce overall dependence on imports and increase overall productivity; It will also contribute to carbon credit and food security in the long-run. The dried biomass can also be used as inputs for animal feed and other useful products such as paper. In this regard, the overall management plan to control and use the WH weed can help the country realize its ecological and socio-economic benefits. It is also a potential response to sustainable green development strategies launched nationwide.

## 4. Conclusions and recommendations

This preliminary study provides a comprehensive overview of WH induced problems and challenges on lake Tana while contributing to the paradigmatic shift of considering the weed as an opportunity rather than a threat. The economic projections made identified the potential economic valuation related to the production of a standard biomass feedstock and biomethane or bioethanol and or organic agro-fertilizer. The results show that employing WH as conventional biomass could economically produce yearly 0.71 million tons at $ 24.40 /ton dry mass, even without subsidies. It also shows that based on the annual dry biomass generation capacity in lake Tana and following the standard biorefinery process protocols, the predictions indicate that the economic potential of converting WH biomass into 38.8 billion litters of biomethane alone to be at $ 38.8 million, 74.2 million litters of bioethanol alone at $ 51.9 million, and 0.261 million tons organic agro-fertilizer alone at $ 130.5/78.3 million as a partial substitute for Anhydrous Ammonia or Muriate of Potash (MOP) fertilizers. These projections show that a high economic potential as biomethane, bioethanol, and organic fertilizer might help Ethiopia; save foreign currency on oil and fertilizer imports. Therefore, as seen in this proposed life cycle cost-benefit analysis, WH biomass is a relatively untapped and cost-effective resource for value-added products with positive environmental and socio-economic advantages.

Furthermore, the findings have significant policy implications. First, because lake Tana is the Nile's source, it's essential to use this research to warn of the dangers of weeds spreading to the Grand Ethiopian Renaissance Dam. Second, in terms of environmental and socio-economic performance, the coupled action of management and utilization scenario as a biorefinery feedstock is a better policy alternative than the existing practice of eliminating the WH weed and disposing of it in landfills; and hence deserves to be promoted. Also, existing control expenses incurred by small stakeholders might be regarded as ecological credit for weed harvesting and biorefineries. And, if future ecological subsidies are provided or well quantified by the government, this will help reduce production costs in the biorefineries and make its investment more attractive.

## Availability of data and materials

The data set supporting the this article is included within the article.

## Declaration of Competing Interest

The authors declare that they have no competing interests.

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