

A comprehensive policy framework for unlocking the potential of water hyacinth in Ethiopia's circular bioeconomy

Derese T. Nega ^{a,b,c,*}, Venkata Ramayya Ancha ^a, Flavio Manenti ^b, Zafar Adeel ^c

^a *Jimma Institute of Technology, Faculty of Mechanical Engineering, Oromia, Ethiopia*

^b *Politecnico di Milano University, Department of Chemistry, Materials and Chemical Engineering "Giulio Natta" (DCMC), Polimi, Italy*

^c *Pacific Water Research Center, Simon Fraser University, Canada*

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ABSTRACT

The invasive water hyacinth (WH), *Eichhornia crassipes*, poses a severe environmental and economic threat to Ethiopian water bodies, particularly in the Rift Valley water bodies and Lake Tana. Known for its rapid proliferation, WH outcompetes native vegetation, doubling its coverage every 13 days, and has the potential to produce 140–350 tons of dry weight per hectare/annum. Lake Tana's northern shore alone bears the brunt of this issue, with an estimated 50,000 hectares of affected areas in Lake Tana alone covering approximately 130 km of lakeshore length as of 2015, apart from other lakes. In response to this pressing concern, the present study is dedicated to formulating a comprehensive circular bioeconomy policy framework focusing on effectively utilizing WH biomass. This innovative framework aims to convert WH biomass into valuable biofuels and other products, acknowledging its potential for environmental mitigation. It integrates diverse policy instruments – informational, economic, cooperative, and regulatory – to encourage sustainable WH biomass production and processing. With a focus on fostering economic advantages for local communities, the framework tackles challenges and outlines implementation strategies, highlighting the importance of international collaboration and robust monitoring systems. Success depends on alignment with existing policies related to environmental protection, energy production, and economic development. The framework unlocks economic, social, and ecological benefits and emphasizes stakeholder collaboration, community participation, and international cooperation. It offers a proactive approach to managing the invasive WH threat sustainably, transforming adversity into sustainable growth. Furthermore, it serves as a model for other countries facing similar challenges, contributing to the global shift towards a circular bioeconomy.

1. Introduction

Water hyacinth (WH) is an invasive aquatic weed that has become a major environmental and economic problem in Ethiopia, causing damage to marine ecosystems, impairing water quality, and disrupting navigation and irrigation systems (Dersseh et al., 2019b). The rapid spread of the invasive WH weed in Ethiopia's Lake Tana, which contributes 60% of the Nile's source (Nega et al., 2021) and other rift valley lakes (FDRE, 2015; Hordofa and Abdi, 2022; Yigermal and Assefa, 2019), has led to significant biodiversity losses and disruption of ecosystem services. The plant is known for its fast growth rate, high reproductive capacity, and ability to form dense mats on water surfaces, which can interfere with aquatic ecosystems, the depletion of oxygen levels, water transport, and irrigation systems (Nega et al., 2021). The plant species have also been linked to environmental degradation, loss of biodiversity, and negative impacts on human health and livelihoods.

Moreover, WH also poses economic challenges by reducing water availability for irrigation and navigation and interfering with fishing activities. These challenges have made WH a significant concern for policymakers and researchers in Ethiopia. However, recent research has shown that WH has enormous potential for biofuel generation and environmental mitigation through the circular bioeconomy biorefinery approach (Nega et al., 2022).

A biorefinery is a facility that uses renewable biomass feedstocks to produce a range of value-added products, including biofuels (bioethanol, biogas, and biodiesel), bioplastics, fertilizers, chemicals, and materials that can replace fossil fuels and reduce greenhouse gas emissions (Barragán-Ocaña et al., 2023; Takkellapati et al., 2018; Nega et al., 2021).

Biorefinery-based solutions have emerged as a promising approach to address the challenges (Harun et al., 2021). Therefore, the control

and utilization of WH biomass as biorefinery feedstock have been identified as critical priorities for Ethiopia's sustainable development (Nega et al., 2022). WH biomass can yield an annual average of 140–350 tons of dry weight per hectare (Gunnarsson and Petersen, 2007; Wang et al., 2019; Hronich et al., 2008). It offers a promising and sustainable biorefinery feedstock for value addition within the circular bioeconomy framework, effectively transforming a threat into an opportunity. It can provide multiple benefits, including reducing the environmental impact of WHs, generating renewable energy, and creating new economic opportunities in the circular bioeconomy framework. However, implementing biorefinery-based solutions requires a comprehensive policy framework to ensure their sustainability and effectiveness (Harun et al., 2021; Nega et al., 2021, 2022).

Nevertheless, the challenge of dealing with invasive WH in Ethiopia has been exacerbated by past efforts being short-lived and uncoordinated, as well as the weak legal and institutional environment for managing these threats (Malo et al., 2010; Nega et al., 2022). Furthermore, the threat of climate change only adds urgency to the need for a comprehensive policy framework to address the WH problem (Mitike et al., 2016; Yara et al., 2019). Several studies have explored the potential of the biorefinery approach for WH utilization in Ethiopia. For example, a study by Anantachaisilp et al. (2021) found the potential of WH for the production of bioethanol, biomethane, and compost in Ethiopia and found that the plant had a high potential for bioethanol production. Another study explored the potential of WH for the production of bioplastics in Ethiopia and found that the plant had a high potential for producing biodegradable plastics (Ilo et al., 2020).

Despite the potential of the circular bioeconomy approach for WH utilization in Ethiopia, several challenges need to be addressed to realize its full potential. These challenges encompass technical aspects concerning the conversion of plant material into value-added products and social, economic, and policy-related hurdles linked to implementing this approach (Nega et al., 2021). Critical challenges associated with implementing the circular bioeconomy approach include inadequate policies and regulations for WH management and circular bioeconomy implementation, limited stakeholder engagement, and a need for more financing mechanisms. In particular, the lack of comprehensive policies and regulations poses a significant obstacle. At the same time, limited awareness and knowledge among stakeholders, including the government, private sector, and local communities, hinder the widespread adoption of the biorefinery circular bioeconomy approach.

Previously, there has been a notable absence of policy formulation in this domain, primarily due to its inappropriateness or incompleteness. Previous efforts have predominantly concentrated on controlling invasive species and environmental management, disregarding the untapped potential of utilizing their biomass for value-added products and adopting a circular bioeconomy perspective (Nega et al., 2022). This study bridges the gap by proposing various policy instruments to effectively address these challenges and facilitate the developing and implementing of the circular bioeconomy approach for invasive WHs in Ethiopia. These policy instruments span information, economic, cooperative, and regulatory measures. Information policy instruments aim to enhance awareness and understanding of the potential of the biorefinery approach among stakeholders. Economic policy instruments aim to provide investment incentives for adopting this approach. Cooperative policy instruments promote collaboration and coordination among stakeholders, while regulatory policy instruments ensure compliance with relevant regulations and standards.

The proposed framework strongly emphasizes the active participation and collaboration of diverse stakeholders, including government agencies, private sector actors, civil society organizations, and local communities. It considers the legal and regulatory framework, technical capacity, market access, and stakeholder engagement to fully realize the biorefinery circular bioeconomy potential of WHs in Ethiopia, as illustrated in Fig. 1, which presents a theory of change. This theory of

change provides a strategic framework for addressing the challenges of WH control and utilization in Ethiopia by implementing a circular bioeconomy policy framework. By focussing on developing a robust policy framework, fostering stakeholder engagement, and building capacity, the proposed framework aims to optimize the benefits of WH while mitigating its negative impacts. Successful implementation of these measures is expected to result in sustainable WH management, renewable energy generation, and positive socioeconomic outcomes.

The study's significance lies in proposing a circular bioeconomy policy framework designed to address the WH problem comprehensively. As of today, there has yet to be a reported specific and versatile policy framework in the Ethiopian or Sub-Saharan African context. The research underscores the potential of WH as a feedstock for biofuel generation and environmental mitigation, positioning itself as a model for other countries dealing with similar challenges posed by invasive species. It aligns with global sustainability goals and climate resilience strategies, emphasizing the transformative potential of circular bioeconomy approaches. Ultimately, this study provides a blueprint for countries facing similar invasive species challenges, emphasizing sustainable management, renewable energy generation, and positive socioeconomic outcomes.

2. Context and background

Ethiopia, located in East Africa, is known for its rich cultural legacy and diverse landscapes. The country has seen significant development and transformation in recent years, with a focus on long-term economic growth and poverty reduction (Tenzing and Conway, 2022). This section examines key indicators of policy initiatives, agricultural productivity, poverty and economic growth, energy availability, and the scale of Ethiopia's WH problem, highlighting the country's successes, challenges, and possibilities for long-term development.

2.1. Key indicators and policy initiatives

Ethiopia's key indicators provide insights into the country's socioeconomic landscape. With a population of approximately 120 million people (Tenzing and Conway, 2022), Ethiopia possesses a diverse and vibrant society. In 2022, the country's GDP growth rate experienced a slight decline to 5.3% from 5.6% in 2021. However, it remained above the East Africa average of 4.7% in 2021 and 4.4% in 2022. The main growth drivers were the industry and services sectors, while private consumption and investment played vital roles in stimulating demand. Inflation rose from 26.6% in 2021 to 34% in 2022 (Calderon et al., 2022). The factors contributing to this inflationary pressure included internal conflict (ongoing civil war), drought, and the effects of Russia's invasion of Ukraine on commodity prices. These factors adversely impacted both growth and inflation. Furthermore, the fiscal deficit expanded to 4.2% of GDP in 2022 from 2.8% in 2021, primarily due to increased defense spending and weak revenue performance (African Development Bank, 2023). Addressing challenges such as inflation, which reached approximately 14% in 2021, is crucial to ensure stable economic conditions. Additionally, Ethiopia's Human Development Index for 2021 stood at 0.485, indicating the need for further improvements in education, healthcare, and other human development indicators (African Development Bank, 2023).

Ethiopia has implemented policy initiatives to drive economic growth and alleviate poverty. The Growth and Transformation Plan (GTP) outlines a comprehensive strategy prioritizing sustainable and inclusive development. Key elements of this plan include infrastructure development, investment in human capital, and the promotion of industrialization (Endris and Kassegn, 2022). The government has emphasized establishing and managing industrial parks across the country, facilitated by the Industrial Parks Development Corporation (IPDC). These parks act as catalysts for attracting foreign investment and

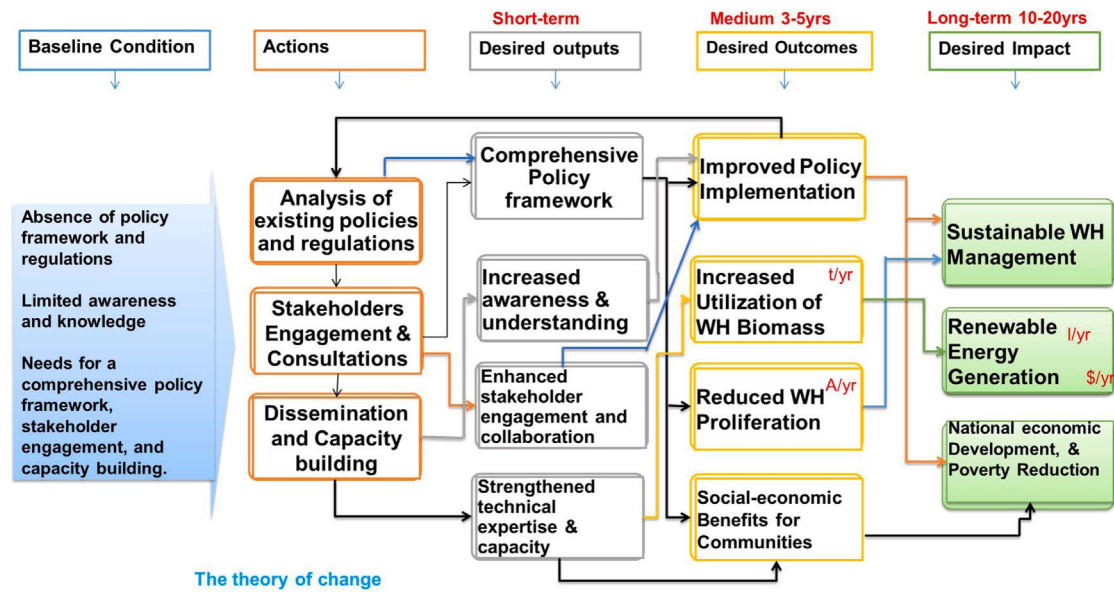


Fig. 1. Theory of change for addressing WH challenges through circular bioeconomy policy framework.

promoting export-oriented manufacturing industries, fostering manufacturing, foreign direct investment, and export growth (Endris and Kassegn, 2022).

Furthermore, Ethiopia launched the Homegrown Economic Reform Agenda in 2019, which aims to attract foreign investment, improve the business climate, and foster sustainable economic growth. Leveraging its strategic location, abundant resources, and emerging manufacturing sector, the Ethiopian government seeks to create employment opportunities and diversify the economy (Okereke et al., 2019). These policy initiatives reflect Ethiopia's commitment to transforming its economy and achieving sustainable development.

2.2. Poverty and economic growth

A large portion of the population in Ethiopia lives below the poverty line, and income inequality remains a pressing issue (ESCAP et al., 2017; World Bank, 2020). According to the World Bank, Ethiopia's poverty rate stands at around 30%, with a significant portion of the population living below the poverty line (Manuh and Yemeru, 2019; World Bank, 2020). Limited access to education, healthcare, infrastructure, and employment opportunities contributes to the persistence of poverty in the region. However, the country has made notable progress in recent years in terms of economic growth (World Bank, 2020). The Ethiopian government has implemented various development strategies and initiatives, such as the Growth and Transformation Plan, to promote economic growth, create employment opportunities, and alleviate poverty (Shapiro, 2019). These efforts have contributed to a steady increase in GDP and improvements in various socio-economic indicators (World Bank, 2020). The country's economy has experienced consistent growth, averaging around 8% in recent years (Coutts and Laskaridis, 2019). The Ethiopian government has implemented poverty reduction programs and invested in agriculture, industry, and services to stimulate economic growth and reduce poverty. Foreign direct investment and development assistance have also played a crucial role in promoting economic development and poverty reduction in the country (Neglo et al., 2021). Similarly, countries like Kenya, Rwanda, and Tanzania have also witnessed notable economic progress, attracting investments across sectors such as agriculture, manufacturing, and services (Lopes and te Velde, 2021).

2.3. Agricultural production

Agriculture plays a pivotal role in Ethiopia's economy, contributing approximately 50% to its GDP (Zerssa et al., 2021). Most of the population relies on agriculture for their livelihoods, with smallholder farming being the predominant form of agricultural activity (World Bank, 2020). The country's diverse agro-climatic conditions support the cultivation of various crops. Ethiopia is renowned for its coffee production and is one of the world's top coffee exporters. Moreover, the agricultural sector produces cereals (such as maize and teff), oilseeds (such as sesame and sunflower), pulses (such as lentils and chickpeas), livestock, and horticulture products (Salami et al., 2010; Eshete et al., 2020; World Bank, 2020). However, agricultural productivity in the country faces several challenges. Limited access to modern inputs, such as improved seeds and fertilizers, inadequate irrigation infrastructure, low mechanization levels, and vulnerability to climate change and weather variability, all hinder agricultural production (Yigezu Wendimu, 2021; Abebe et al., 2018; Ali et al., 2020).

To address these challenges and promote sustainable agricultural practices, the Ethiopian government has implemented various initiatives. These include providing smallholder farmers access to improved seeds, fertilizers, and irrigation systems (Canton, 2021). Efforts have also been made to diversify the agricultural sector and promote sustainable development, such as cultivating high-value crops and enhancing livestock production. Agriculture plays a crucial role in Ethiopia's economy, employing a significant portion of the population and contributing to GDP and export earnings.

Improving agricultural productivity and market access is vital for poverty reduction and economic growth. Through the Agricultural Transformation Agency (ATA) (Diriba, 2020), the government has implemented programs to modernize farming practices, enhance access to finance and technology, and strengthen value chains. Additionally, investments in irrigation systems, research and development, and extension services support smallholder farmers and boost agricultural production. Empowering farmers, promoting sustainable practices, and expanding agro-processing contribute to improved livelihoods and increased incomes (Debelo, 2020).

2.4. Energy availability

Access to reliable and affordable energy is crucial for socio-economic development in Ethiopia and East Africa. However, most of the population, especially in rural areas, heavily relies on traditional biomass

Table 1
Potential and exploited source of energy in Ethiopia (Tiruye et al., 2021).

Source	Unit	Exploitable potential	Percentage exploited (%)
Hydropower	GW	45	≈7
Solar (day)	kWh/m ²	5.26	<1
Wind	GW m/s	1350	<1
Geothermal	GW	7	<1
Biomass	Million tons/yr	75	<50
Biogas	Household	1–3 million	<1
Fire Wood	Million tons/yr	1120	30
Agricultural waste	Million tons/yr	15–20	30
Natural Gas	Billion m ³	113	0
Coal	Million tons	300	0
Oil shale	Million tons	253	0

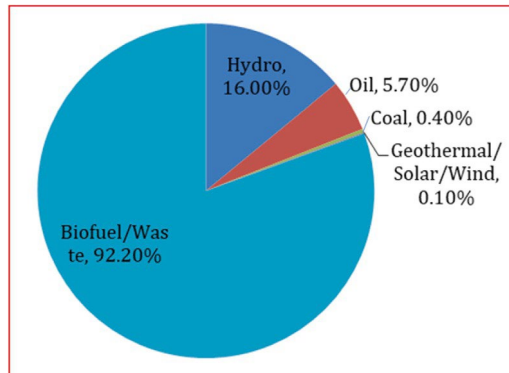


Fig. 2. The distribution of the total primary energy supply in Ethiopia as of 2015 (Tiruye et al., 2021).

fuels, hindering productivity, healthcare, and education. Efforts are underway to expand access to modern energy sources, improve infrastructure, and develop renewable energy. Ethiopia is leveraging its abundant renewable energy resources, such as the Grand Ethiopian Renaissance Dam, along with geothermal, wind, and solar energy, to diversify its energy mix and provide clean and reliable energy to both rural and urban areas (Van de Graaf, 2021; Gu et al., 2021).

Despite the vast potential of renewable energy resources in Ethiopia, their development still needs to be explored mainly, apart from biomass fuel. The country boasts a hydropower capacity of 45 GW, wind power capacity of 10,000 MW, geothermal capacity of 7 GW, and an average solar energy yield of 5.26 kWh per square meter per day (Tahiru et al., 2023). However, the challenge lies in ensuring equitable distribution of energy resources and extending access to rural areas. Rural areas need more electricity access, with only 32% coverage compared to 92% in urban areas. In 2019, 55.2% of the population lived without access to electricity (Tahiru et al., 2023; Tiruye et al., 2021). Table 1 outlines Ethiopia's exploitable potential of various energy resources.

Like other African countries, Ethiopia heavily relies on biomass-based energy, primarily for household purposes. Waste and biomass account for the largest share (92.2%) of the total primary energy supply, followed by oil (5.7%) and hydropower (1.6%) (see Fig. 2) (Tahiru et al., 2023). Rural areas in Ethiopia lack electricity access, with only 32% coverage, while urban areas have a 92% connection rate. The government has set a target of achieving 100% electricity coverage by 2030, up from 45% in 2018, with an annual increase of 1.7% from 2010 to 2019 (Tahiru et al., 2023; Tiruye et al., 2021). The focus is on harnessing abundant renewable energy resources such as hydropower, solar, and wind to increase energy availability and foster sustainable development.

Ethiopia is actively pursuing various bioenergy sectors to complement traditional energy sources and reduce dependence on fossil fuels. Initiatives such as biogas, bioethanol, and waste-to-biofuels projects are

being implemented to diversify the energy mix and promote sustainable energy practices (Hailu and Kumsa, 2021). These initiatives hold the potential to create new economic opportunities and improve energy access in both rural and urban areas. Table 2 provides an overview of Ethiopia's biomass power plants' technology, presenting the installed and ongoing biomass power plants, their power generating capacities, and commercial operation dates, demonstrating the country's commitment to a diversified energy mix.

2.5. The scale of the WH problem in Ethiopia

Ethiopia's WH problem is significant and has profound ecological and economic implications. It affects various water bodies, including Lake Tana, the Awash River, the Blue Nile River, and several lakes in the Rift Valley region (refer to Fig. 3 and Table 3). The dense mats of WH obstruct waterways, degrade water quality, and disrupt aquatic ecosystems. Fishing activities, irrigation systems, and navigation are adversely impacted, leading to economic losses and affecting the livelihoods of communities dependent on water resources (Dersseh et al., 2019b; Nega et al., 2022).

The invasion of WH in Lake Tana has resulted in extensive coverage, especially along the shores and bay areas, disrupting the lake's ecological balance by blocking sunlight, reducing oxygen levels, and impeding the growth of native aquatic plants (Dersseh et al., 2019b; Nega et al., 2022; Ayele and Atlabachew, 2021). The negative impact extends to fishing activities and transportation routes, affecting the livelihoods of local communities (Nega et al., 2022).

Similarly, the spread of WH in the Awash River (Assegide et al., 2022), and the Blue Nile River (Asmare et al., 2020) hampers flow dynamics, increases flood risks, interferes with agriculture, and disrupts hydroelectric power generation. Navigation is impeded, transportation costs rise, and trade and economic activities suffer (Dechassa and Abate, 2020a).

Lakes in the Rift Valley region, such as Ziway, Abaya, Chamo, and Awassa, have also experienced significant infestations of WH, leading to ecological disruption, a decline in fish populations, and economic losses for fishing communities (Firehun et al., 2014; Gedefaw and Gondar, 2018). Table 3 provides an estimate of the infestation level and overall coverage of WH in Rift Valley water bodies in 2014.

The Koka Reservoir on the Awash River, a vital storage facility for irrigation and hydropower, faces capacity reduction and interference with operations due to WH invasion (Bezu, 2020; Kitunda, 2017), impacting agriculture, electricity generation, and community livelihoods.

The WH invasion is not limited to major water bodies but also affects smaller rivers, streams, and ponds across Ethiopia. These water sources are vital in providing water for domestic use, livestock, and small-scale irrigation. The growth and spread of WHs disrupt the ecological balance, impair water quality, and hinder local communities' access to clean water (Nega et al., 2022). Efforts to address the WH problem involve various control and management strategies, including physical removal, biological control, and herbicide application (Dersseh et al., 2019b). However, the extensive coverage of WH in multiple water bodies necessitates comprehensive and sustained efforts to mitigate its negative impacts effectively (Nega et al., 2021, 2022).

Recognizing the magnitude of the issue, utilizing WH as a feedstock for biofuel generation and employing the biorefinery circular bioeconomy approach for environmental mitigation has emerged as a promising solution (Nega et al., 2022). This approach offers opportunities to control the spread of WH while generating renewable energy, creating employment, and promoting sustainable development in Ethiopia and the broader East Africa region. Integrating the circular bioeconomy concept into WH management can yield socioeconomic and environmental benefits, contributing to poverty alleviation, economic growth, and ecological sustainability (Nega et al., 2022).

Table 2

Overview of the biomass power plants' technology in Ethiopia (Hailu and Kumsa, 2021).

Power plants	Location	Installed capacity (MW)	Category	Commercial Operation Date (COD)
Reppie waste-to-energy plant	AA	25	Utility	2018
Finchaa Sugar Factory Bagasse	Finchaa	31	Embedded	1998, 2012
Wonji Sugar Factory Bagasse	Adama	31.5	Embedded	2013
Omo Kuraz II Bagasse	Kuraz	60	Embedded	2017
Tendaho Sugar Factory Bagasse	Asaita	60	Embedded	2017
Omo Kuraz III Bagasse	Kuraz	60	Embedded	2018
Total		267.5		
Tana Beles I Bagasse	Agew Awi	30	Embedded	Under construction Expected COD = 2020
Omo Kuraz I Bagasse	Kuraz	45	Embedded	Under construction Expected COD = uncertain
Omo Kuraz V Bagasse	Kuraz	120	Embedded	Under construction Expected COD = uncertain
Tana Beles II Bagasse	Agew Awi	30	Embedded	Under construction Expected COD = uncertain
Grand total		492.5		

Table 3

Estimated infestation level and overall coverage of WH in Rift Valley water bodies in 2014, Firehun et al. (2014).

Water bodies	Altitude	Mean fresh weight (kg/m ²)	Mea plant population (Plants/m ²)	Infestation level	Observed coverage (%)
Aba-Samuel Dam	2052	7.0	67	Low-High	46
Lake Ellen	1700	44.0	276	High	100
Lake Elltoke	1700	42.0	248	High	92
Lake Koka	1589	23.0	298	Free-High	37
Koka Dam	1580	21.0	308	Free-High	30
Wonji-Shoa sugar factory	1500	3.0	23	Free-Low	<7
Metahara sugar factory	950	0.0	0	Free	0
Melka Hida	1450	6.0	58	Free-Low	20
Afer Gideb	1539	15.0	261	Free-High	55
Taree	1580	13.0	211	Medium-High	58
Awash	1460	10.0	186	Medium-High	42
Lake Abaya	1285	0.1	6	Free-Low	0

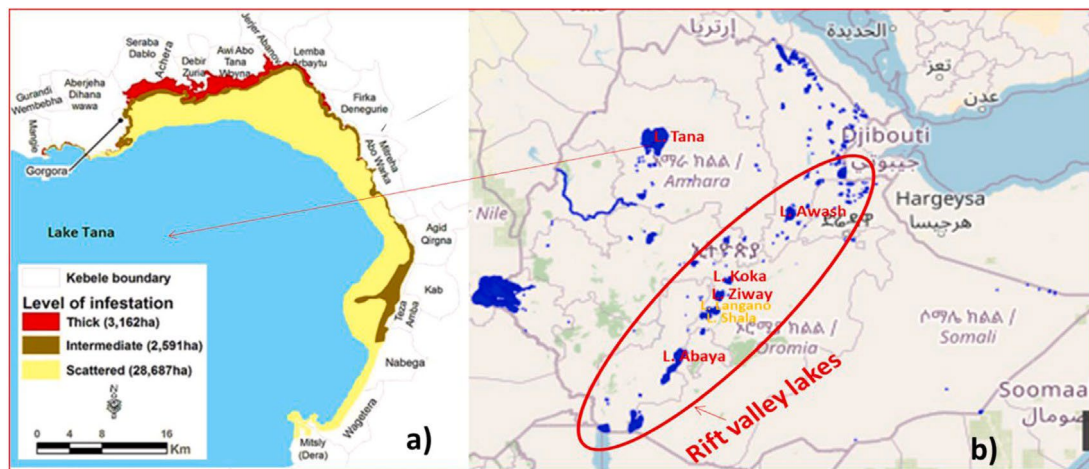
**Fig. 3.** Extensive Coverage of WH in Ethiopian Water Bodies, highlighting the proliferation of this invasive aquatic weed in Lake Tana (a: Nega et al., 2021) and Rift Valley Lakes (b: Dersseh et al., 2019b), and emphasizing the ecological and economic implications.



Fig. 4. WH Circular Bioeconomy: Control vs utilization through biorefinery benefits towards the WEF E nexus.

3. WH circular bioeconomy: Benefits towards WEF E nexus

The integration of control measures and the utilization of harvested WH biomass through circular bioeconomy practices offer numerous sustainability benefits across various dimensions (Omran and Baek, 2022), addressing the Water-Energy-Food-Ecosystem (WEFE) nexus (Bazzana et al., 2023). Fig. 4 depicts the positive impacts of WH control and utilization on sustainable WH management, energy and materials, water, agriculture, ecosystem, and community.

3.1. Sustainable WH management

Mechanical harvesting methods are crucial in sustainably managing invasive WH weeds. Techniques like aquatic weed harvesters or dredgers effectively remove WH biomass from water bodies, contributing to control efforts (Nega et al., 2021). These control measures mitigate the negative environmental impacts of WH infestations and support sustainable WH management by preventing the spread of invasive species and promoting the growth of native flora and fauna (Hronich et al., 2008). Restoring WH-infested areas through control measures contributes to phytoremediation, improving water quality, and restoring ecosystem balance. Additionally, the control of WH creates opportunities for tourism and recreational activities, enhancing economic benefits and supporting the sustainable utilization of WH-infested water bodies (Hronich et al., 2008; Neglo et al., 2021; Nega et al., 2022).

3.2. Sustainable energy & materials

Using harvested WH biomass in the biorefinery framework presents sustainable energy and materials production opportunities (Harun et al., 2021; Nega et al., 2022). Biorefinery conversion technologies, such as anaerobic digestion, fermentation, or thermochemical processes, can extract valuable compounds from WH biomass. These processes result in the production of biofuels, such as bioethanol or biodiesel, which serve as sustainable alternatives to fossil fuels, reducing greenhouse gas emissions and promoting energy security (Culaba et al., 2022; Harun et al., 2021). Moreover, WH biomass can be converted into biochar, a carbon-rich material that can improve soil fertility and sequester carbon, contributing to sustainable land management practices. Furthermore, extracting bioplastics and biochemicals from WH biomass offers sustainable alternatives to conventional plastics and

chemical products, reducing environmental impacts and supporting the transition towards a circular economy (Culaba et al., 2022; Harun et al., 2021; Nega et al., 2021).

3.3. Sustainable water

The control and utilization of WH contribute to sustainable water management. By removing WH biomass from water bodies, water quality improves as the excessive accumulation of organic matter is reduced (Elbasiouny et al., 2021; Yan et al., 2017). This, in turn, enhances the ecological functioning of the water ecosystem and supports the sustainable use of water resources. Additionally, the utilization of WH biomass for water treatment purposes can provide a cost-effective and environmentally friendly solution for nutrient removal and wastewater purification. WH biomass as a natural filter media or adsorbent material can effectively remove pollutants, improving water quality and supporting sustainable water practices (Harun et al., 2021).

3.4. Sustainable agriculture

The utilization of harvested WH biomass in agriculture offers multiple sustainability benefits. WH biomass can be processed into organic fertilizers, which provide essential nutrients to crops while promoting soil health and fertility (Nega et al., 2022). Incorporating organic fertilizers derived from WH biomass reduces the reliance on synthetic fertilizers, mitigating the negative environmental impacts of their production and use. Additionally, WH biomass can be used as animal feed, contributing to sustainable livestock production and improving food security. The utilization of WH biomass in agriculture fosters nutrient cycling, reduces waste, and supports sustainable agricultural practices (Harun et al., 2021; Nega et al., 2021).

3.5. Sustainable ecosystem

The successful control and utilization of WH biomass positively impacts the ecosystem (Yan et al., 2017). By preventing the disposal of harvested biomass in WH-infested water bodies, greenhouse gas (GHG) emissions are reduced. Carbon sequestration in WH biomass through utilization or conversion into biochar effectively contributes to carbon fixation and reduced GHG emissions (Feng et al., 2020). This process supports sustainable land management and climate change mitigation efforts. Furthermore, the control and utilization of WH

biomass promote ecological restoration by reducing competition with native species, restoring biodiversity, and improving overall ecosystem health and resilience (Wang et al., 2019; Harun et al., 2021).

3.6. Sustainable community

The control and utilization of WH biomass create opportunities for sustainable community development. Establishing biorefinery systems and related industries generates green jobs, fostering economic growth and providing sustainable livelihoods for local communities (Harun et al., 2021). The involvement of communities in WH control and utilization activities, fishing, and recreational activities promotes social cohesion, participation, and empowerment. This community engagement contributes to the sustainable management of WH-infested areas and enhances the well-being of local populations (Wang et al., 2019; Harun et al., 2021).

Overall, in Fig. 4, the implementation of circular bioeconomy practices for the control and utilization of WH presents a range of substantial advantages within the WEFEE nexus (Bazzana et al., 2023; Ubando et al., 2020). By incorporating measures for controlling WH growth and harnessing its biomass, sustainable management of WH is achieved, benefiting various dimensions such as energy and materials, water resources, agriculture, ecosystems, and community development (Wang et al., 2019; Harun et al., 2021). These practices contribute significantly to restoring water bodies infested with WH, improving water quality, facilitating sustainable energy production, enhancing agricultural techniques, promoting ecosystem health and resilience, and fostering the overall development of communities. Within a biorefinery framework, the control and utilization of WH provide a comprehensive and scientifically grounded approach to tackle the WEFEE nexus and advance sustainability objectives (Nega et al., 2022, 2021).

4. Global insights: Lessons in invasive WH management, biorefinery features, and legal frameworks

Invasive WH and water pollution are significant environmental challenges worldwide (Harun et al., 2021). Managing invasive WH requires comprehensive and innovative approaches, including early detection, integrated strategies, and collaboration. Insights gained from previous management experiences emphasize the importance of early detection, integrated strategies, and collaboration (Djihouessi et al., 2023). Biorefinery technologies offer a sustainable means to utilize WH biomass effectively, contributing to environmental preservation and resource efficiency (Harun et al., 2021; Wang et al., 2019). Robust legal frameworks at international and national levels underscore the global commitment to combat invasive species and protect ecosystems.

4.1. Features of WH biorefinery-based approaches

Invasive WH biorefinery-based approaches have emerged as a promising solution to tackle the environmental and socio-economic challenges posed by the proliferation of this weed. At the heart of WH biorefinery-based approaches lies a well-defined framework involving a series of processes. These processes include pretreatment, hydrolysis, fermentation, and purification, which collectively transform the abundant biomass of WH into various valuable products. Converting this invasive plant into value-added products holds immense promise for environmental restoration, sustainable energy generation, and economic development (Nega et al., 2022, 2021).

Global significance and challenges. On a global scale, adopting biorefinery-based approaches for WH utilization offers significant potential in addressing various socio-economic and environmental challenges. Studies by Sindhu et al. (2017) emphasize how such approaches can contribute to sustainable development and ecological balance. However, several obstacles hinder the widespread implementation of these approaches.

One of the primary challenges is the lack of technical expertise in WH biorefinery processes, as highlighted by Karouach et al. (2022). Additionally, financial constraints hinder the development and operation of biorefineries, as noted by Harun et al. (2021). Moreover, transportation and logistics issues, including inadequate infrastructure and road networks, make it challenging to transport WH biomass from harvesting sites to biorefinery plants, as highlighted by Venkatesh (2022).

Insufficient institutional support, limited public awareness, and weak stakeholder engagement are key challenges that hinder the widespread adoption of biorefinery-based approaches for WH utilization, particularly in Ethiopia (Nega et al., 2022). Benti et al. (2021) reports these challenges, emphasizing the need for effective policies and initiatives to overcome them. Although policy frameworks exist in Ethiopia to promote renewable energy and waste utilization, they lack specific provisions for WH biomass utilization, as noted by Hameer and Ejigu (2020) and Hirpe and Yeom (2021). The lack of comprehensive policies and regulations for the management and utilization of invasive WH in Ethiopia is also highlighted by Ingwani et al. (2010) and Karouach et al. (2022).

The role of comprehensive policies. To facilitate the successful utilization of WH through biorefinery-based approaches, policy frameworks need to include provisions for research and development, capacity building, stakeholder engagement, and financing mechanisms. Metawie* (2004), Mondal et al. (2010), Uitto (2004) and Zikargae (2022) suggest these essential components for effective WH utilization. Biorefinery-based approaches offer a wide range of value-added products from WH biomass, including biofuels, bioplastics, animal feed, and fertilizer, as reported by Ashokkumar et al. (2022), Goswami et al. (2022), and Sindhu et al. (2017).

Adopting biorefinery-based circular bioeconomy approaches for WH utilization brings multifaceted benefits, including employment opportunities, poverty alleviation, and enhanced environmental sustainability (Bajpai and Nemade, 2023; Ganorkar et al., 2021). Effective stakeholder engagement, particularly with local communities, is pivotal for success (Dowling et al., 2016; Harun et al., 2021). Capacity-building programs covering training and education are imperative to address the shortage of technical expertise in biorefinery-based approaches (Weber, 2018).

Innovative financing mechanisms, such as public-private partnerships and microfinance schemes, can help overcome the financial resource constraints associated with implementing circular biorefinery approaches, as suggested by Ketkar and Ratha (2008) and Qadir et al. (2021). Biorefinery-based solutions for WH control and utilization present opportunities for economic growth, renewable energy generation, and environmental pollution reduction (Bajpai and Nemade, 2023). These solutions yield value-added products like biofuels, biochar, and bioplastics (Barragán-Ocaña et al., 2023). Moreover, they can improve soil fertility, increase crop productivity, and mitigate greenhouse gas emissions (Neglo et al., 2021). The biorefinery approach to WH utilization can also serve as an alternative source of raw materials for various industries, including paper, textiles, and chemicals (Bajpai and Nemade, 2023; Nega et al., 2022).

WH biorefinery across different regions. Exploring invasive WH for biorefinery applications has yielded promising results in various regions worldwide. India has implemented the National WH Control and Utilization Program, establishing WH-based biogas plants for electricity generation, cooking, and heating (Bajpai and Nemade, 2023).

Meanwhile, China utilizes WH in microbial fermentation to produce biopolymers, specifically polyhydroxyalkanoates (Sundararaju, 2020). WH contributes to biofertilizer production in Africa through composting and vermicomposting, while the USA investigates bioethanol production through pretreatment, hydrolysis, and fermentation processes (Ganorkar et al., 2021; Bajpai and Nemade, 2023).

Although Africa is in the early stages of utilizing WH for biorefinery purposes, countries like South Africa and Nigeria are making significant strides. The Council for Scientific and Industrial Research (CSIR) in South Africa and the Federal University of Technology in Nigeria have conducted studies showcasing the conversion of WH biomass into biofuels, bioplastics, and biochar (Ilo et al., 2020). Similarly, in Nigeria, the Federal University of Technology has explored WH utilization for biorefinery purposes, producing biogas, bioethanol, and biofertilizers (Ajibade et al., 2013).

Governments globally recognize the potential of WH biorefinery and are taking initiatives to establish industries using WH biomass. In India, the Department of Biotechnology launched the Biorefinery Mission in 2017, focusing on various feedstocks, including WH, for biofuel and bioplastic production (Cherwoo et al., 2024). Under the Chinese Academy of Sciences, China explores WH biomass for biorefinery purposes, producing biofuels, bioplastics, and activated carbon (Ruan et al., 2016). In the USA, the Department of Energy and the University of California, Davis, are researching converting WH biomass into biofuels, bioplastics, and biochar (Gaurav et al., 2020).

4.2. Legal frameworks and control measures of invasive species in different countries

Africa

In many other African countries, WH is a significant environmental problem. The spread of WH negatively impacts fishing, navigation, water quality, and public health (Navarro and Kanyama-Phiri, 2000). To address these challenges, many African countries have enacted laws and regulations to control the spread of WH. For example, the National Environmental Management Act in South Africa prohibits introducing and spreading invasive species, including WH (Affairs, Department of Environmental, 2014; Mashamaite et al., 2020). Similarly, in Nigeria, the National Environmental Standards and Regulations Enforcement Agency (NESREA) enforces environmental laws and regulations, including those related to WH (Suleiman et al., 2019). In addition, various control measures, such as mechanical removal, biological control, and herbicide application, have been implemented to manage WH (Adeoluwa, 2018; Suleiman et al., 2019).

The legal frameworks and control measures related to the utilization or biorefinery of WH in other African countries vary across countries. Kenya has implemented the Water Act of 2016, which focuses on managing, conserving, and controlling water resources, including using invasive aquatic plants for economic development purposes (Adwek et al., 2019). The National Environment Management Authority (NEMA) in Kenya collaborates with stakeholders to develop strategies for sustainable WH management and utilization, including initiatives such as community-based crafts and biogas production (Yara et al., 2019).

In Nigeria, the National Water Resources Bill of 2020 aims to establish a legal framework for the management and sustainable development of water resources, encompassing provisions for controlling invasive species like invasive WH (Castro and Agblevor, 2020; Doro et al., 2020). The Federal Ministry of Environment and other agencies in Nigeria have launched programs to encourage the utilization of WH, promoting its conversion into valuable products such as paper, handicrafts, and biofuels through initiatives like the WH Control and Utilization Programme (Gandhi and Srinivasan, 2020).

South Africa regulates the conservation and management of biodiversity, including invasive species, through the National Environmental

Management: Biodiversity Act of 2004 (Affairs, Department of Environmental, 2014; Mashamaite et al., 2020). This empowers the Minister of Water and Environmental Affairs to identify and regulate invasive species such as WH. Invasive species management plans in South African provinces often include provisions for utilizing or controlling WH, aiming to mitigate its negative impacts while exploring its resource potential (Maruapula, 2020; Mashamaite et al., 2020).

Uganda's National Environment Act of 2019 addresses the protection and sustainable use of the environment, including managing invasive species. The Act grants the National Environment Management Authority authority to regulate and control WH. Uganda has initiated projects, such as the WH Utilization Project in Lake Victoria, which focuses on converting the plant into briquettes, biogas, and organic fertilizers for economic benefit (Kiyemba, 2021; Namaalwa and Byakagaba, 2019).

Even though it is a fragmented legal framework, these legal frameworks and control measures across other African countries aim to regulate the management and utilization of WH while promoting sustainable development and addressing the environmental and socio-economic challenges associated with this invasive plant. Local initiatives, community involvement, and collaboration with stakeholders play significant roles in implementing these measures and exploring the potential of WH for value-added material recovery or biorefinery purposes.

India

In India, invasive WH is a significant environmental problem, affecting many water bodies across the country. The Indian government has enacted laws and regulations to control the spread of WH and other invasive species. For example, the Biological Diversity Act 2002 regulates the conservation and sustainable use of biological resources, including invasive species (Devi and Padmavati, 2016). In addition, the National River Conservation Plan and National Lake Conservation Plan have been implemented to improve the quality of water bodies and prevent the spread of invasive species (Sarkar et al., 2010; Shan et al., 2021). Various control measures, such as manual removal, biological control, and chemical control, have also been used to manage invasive WH in India (Jawed et al., 2022; Bax et al., 2003).

The legal frameworks and initiatives in place to control WH invasion and promote its utilization through biorefinery processes in India are commendable. Environmental legislation, such as the Water (Prevention and Control of Pollution) Act of 1974 and the Environment Protection Act of 1986, empower government agencies to regulate and control the spread of invasive species like WH in water bodies. These laws provide a strong foundation for addressing the issue nationally. State-level initiatives, like the Kerala Hyacinth Control Program, demonstrate proactive measures taken by different states in India to combat WH invasion. These initiatives focus on controlling and managing WH through various methods, including biorefinery. The emphasis on utilizing its biomass shows a progressive approach towards sustainable solutions (Jain, 1984; Thakur, 1997).

The National Biofuel Policy formulated by the Government of India further encourages the production and use of biofuels from various biomass sources, including invasive WH. This policy provides a supportive framework for utilizing WH biomass in biofuel production. It showcases the government's commitment to exploring alternative energy sources and reducing reliance on fossil fuels (Das, 2020). Although specific legislation or policies solely dedicated to WH biorefinery may not exist, the existing legal frameworks and initiatives provide a solid foundation. It is encouraging to see a growing recognition of the potential of WH biomass and the efforts being made to explore its utilization.

China

In China, WH is a significant environmental problem, especially in the Yangtze River basin and the Poyang Lake region. The Chinese government has implemented various legal frameworks and control measures to manage WHs and water pollution. For example, the Law of the People's Republic of China on Prevention and Control of Water Pollution regulates the discharge of pollutants into water bodies (Xiong et al., 2023). In addition, the Chinese government has implemented various control measures, such as manual removal, biological control, and herbicide application, to manage WH (Chen et al., 2020; Yee and Guo, 2021).

USA and Canada

In the USA and Canada, invasive species and water pollution are significant environmental challenges, affecting many water bodies across the country. The governments of the USA and Canada have enacted various laws and regulations to control the spread of invasive species and prevent water pollution. For example, the Clean Water Act in the USA regulates the discharge of pollutants into water bodies (Havel et al., 2015; USDo Interior, 2016). Similarly, the Canadian Environmental Protection Act regulates the discharge of pollutants into water bodies and the introduction of invasive species (Government of Canada, 2021). In addition, various control measures, such as mechanical removal, biological control, and herbicide application, have been used to manage invasive species in the USA and Canada (Smith et al., 2014; Striffling, 2011).

4.3. Invasive WH and global environmental conflicts

The WH problem has led to several international ecological conflicts (Harun et al., 2021). For example, in the 1980s, the WH infestation of Lake Victoria, shared by Kenya, Tanzania, and Uganda, caused significant economic losses and environmental damage (Balirwa et al., 2003). The plant blocked water flow, making it difficult for boats to navigate the lake and causing problems for the fishing industry. There were also concerns that the plant would spread to other waterways in the region (Karouach et al., 2022; Navarro and Kanyama-Phiri, 2000). The WH problem in Lake Victoria led to international cooperation to address the issue. In 1989, the three countries formed the Lake Victoria Environmental Management Project to manage the region's plant and other environmental issues (Navarro and Kanyama-Phiri, 2000). The project involved using biological controls, such as weevils, to reduce the spread of the plant.

In addition to Lake Victoria, the WH problem has caused conflicts in other parts of the world. For example, in the United States, the plant has invaded many waterways, causing problems for navigation and recreation. It has also affected water quality and wildlife habitat. There have been conflicts between states over who should be responsible for controlling the plant and paying for the costs of management (Kriticos and Brunel, 2016; Navarro and Kanyama-Phiri, 2000).

In response to this problem, various invasive WH management methods have been developed. One approach has been the use of biological controls, such as weevils, which have proven to be an effective way of reducing the spread of the plant (Julien et al., 1996; Aguilar et al., 2003; Yara et al., 2019). Other methods have included chemical control, mechanical harvesting, and machinery such as boats and dredgers.

Despite the implementation of these interventions, conflicts have continued to arise over the management of WH. For example, in the United States, there have been disputes between states over who should be responsible for controlling the plant and paying for the costs of management (Karouach et al., 2022; Yara et al., 2019).

Another issue is the effectiveness of the management methods themselves. For example, while biological controls have been successful in some cases, they may not always be appropriate or effective in all situations. Chemical control methods may have negative environmental

impacts and can harm non-target species (Julien et al., 1996; Yara et al., 2019).

In this regard, the WH problem has resulted in significant environmental conflicts, with responses and interventions through invasive WH management methods being a major contributor. While there have been successes in controlling the spread of the plant, challenges remain in finding effective and sustainable management solutions, particularly in the context of international cooperation.

Therefore, the WH problem is an example of how environmental issues can lead to international conflicts. However, it is also an example of how cooperation and collaboration can effectively address these issues. By working together, countries can develop strategies to manage invasive species and protect the environment (Harun et al., 2021; Yara et al., 2019).

4.4. The legal landscape for tackling invasive weeds, including WH, in Ethiopia

The legal framework in Ethiopia related to WH noxious weeds and water pollution is mainly governed by the Environmental Pollution Control Proclamation No. 300/2002 (FDREno. 300, 2002), the Water Resources Management Proclamation No. 197/2000, (FDREno197, 2000; Tekle, 2019), the Plant Protection Proclamation No. 313/2003 (FDREno313, 2003; Tabla-Hernandez et al., 2020). The Plant Breeders' Right Proclamation No. 1068/2017, (FDREno.1068, 2017; Mitike et al., 2016; Tabla-Hernandez et al., 2020). These laws establish legal mechanisms for regulating and monitoring activities that may cause water pollution and the spread of invasive species, including WHs.

According to Mitike et al. (2016), the Environmental Pollution Control Proclamation No. 300/2002 is one of Ethiopia's primary laws governing water pollution, providing clear guidelines for the prevention and control of water pollution. It provides a framework for preventing, controlling, and mitigating air, water, and soil pollution. In relation to WH and water pollution, this proclamation likely includes provisions for monitoring and regulating activities that may contribute to the spread and growth of WH, as well as the discharge of pollutants into water bodies. The Water Resources Management Proclamation No. 197/2000, FDREno197 (2000) is another important law regulating water resource management and ensuring their sustainable use. It establishes mechanisms for the planning, development, and protection of water resources. This proclamation likely includes provisions related to preventing and controlling water pollution caused by invasive species like Invasive WH, considering its impact on the ecological balance of water bodies (Tekle, 2019).

In addition, the Plant Protection Proclamation No. 313/2003 and Plant Breeders' Right Proclamation No. 1068/2017 provide legal mechanisms for the control of noxious weeds like WH and preventing their spread (Tabla-Hernandez et al., 2020). These laws and regulations are crucial for preventing the introduction and spread of invasive species like WH in Ethiopian water bodies. It sets out measures for preventing the introduction and spread of harmful organisms that can affect plants, including WH. It may include regulations for the control and eradication of WH as a noxious weed. While Plant Breeders' Right Proclamation may not directly address WH and water pollution, it could indirectly contribute to regulating plant breeding activities involving WH or other invasive species.

Furthermore, the Fisheries Development, Utilization, and Administration Proclamation No. 315/2003 (FDREno.315, 2003), Ethiopia's National Biodiversity Strategy and Action Plan 2015- FDRE (2015), and the Ethiopian Environmental Policy (Bekele, 2008; Kneeland and Knutson, 2012) further reinforce the government's commitment to protecting the aquatic ecosystem, promoting sustainable use of water resources, and preventing the introduction of foreign species that may harm the environment. These policies and strategies are aimed at conserving the biodiversity of Ethiopia's environment and its ecosystems.

The Ethiopian government has also established institutions such as the Ministry of Water, Irrigation, and Energy, the Environmental Protection Authority, and the Ethiopian Biodiversity Institute to enforce these laws and policies (Bekele, 2008; Hailemariam et al., 2016). These institutions work together to monitor and regulate activities that may cause water pollution and prevent the spread of invasive species like WHs. The concerted efforts of the Ethiopian government and its institutions are critical for conserving the biodiversity of Ethiopia's environment, ecosystems, and aquatic life.

Overall, Ethiopia's legal framework and institutional arrangements demonstrate a solid commitment to protecting the environment and biodiversity, including preventing and controlling invasive species like WH. By enforcing these laws and policies, Ethiopia can promote sustainable use of water resources, protect the aquatic ecosystem, and ensure the long-term health of its environment. However, specific legislation or policies solely dedicated to WH biorefinery may not exist; the existing legal frameworks and initiatives provide a solid foundation. It is encouraging to see a growing recognition of the potential of WH biomass and the efforts being made to explore its utilization.

5. Methods

The study employed a mixed-methods approach, combining both quantitative and qualitative techniques, to establish a comprehensive policy framework for circular bioeconomy initiatives in Ethiopia, with a specific focus on WH control and utilization. The literature review thoroughly examined academic, government, and industry publications to collect pertinent information. The development of a policy framework is substantiated by selected scholarly works, as depicted in (Table 4). Concurrently, policy analysis evaluated existing policies and strategies concerning environmental protection, energy production, biorefinery, and economic development in Ethiopia.

The biorefinery-based approach to WH control and utilization in Ethiopia holds promising potential for generating various value-added products, including biofuels, biofertilizers (such as biochar and bio compost) obtained through nutrient recovery, animal feed, and other relevant outputs. These bioproducts are envisioned to effectively address the escalating demand for renewable energy and sustainable materials while concurrently mitigating greenhouse gas emissions and environmental pollution.

The proposed policy framework was formulated based on the principles of the circular bioeconomy approach, adaptive management, and comprehensive analysis of policy instruments. Valuable inputs from experts and stakeholders representing academia, government agencies, non-governmental organizations (NGOs), and the private sector were thoughtfully incorporated to ensure the resulting framework's feasibility, sustainability, and acceptability.

5.1. SWOT analysis

Conducting a SWOT Strengths, Weaknesses, Opportunities, and Threats analysis for Ethiopia's WH biorefinery circular bioeconomy approach provides valuable insights into its current status and potential future. This comprehensive policy framework aimed at harnessing the potential of invasive WH for biofuel generation and environmental mitigation reveals a multifaceted landscape. The analysis reveals several critical aspects, as illustrated in Fig. 5. The strengths of the WH biorefinery approach in Ethiopia are rooted in the abundant availability of WH as a feedstock, offering the potential for producing biofuels and value-added products. This approach aligns seamlessly with the circular bioeconomy model, fostering economic growth and reducing dependency on fossil fuels. Sustainable practices and collaboration among stakeholders contribute to effective resource management, climate resilience, the creation of green jobs, and environmental restoration. This presents a significant opportunity to address the growing demand for renewable energy sources and sustainable materials. It also encourages

international collaboration, the diversification of bioproducts, empowerment of local communities, investments in research and development (R&D), technological advancements, market growth, investment opportunities, engagement with the public-private sector, skills development, meeting GHG emission reduction targets, and realization of the circular economy.

Nevertheless, there are areas for improvement to contend with, including capital resource and capacity constraints, challenges associated with long-term implementation complexity, the need for a comprehensive policy framework, regulatory hurdles, funding limitations, uncertainties related to environmental impact, limited market demand for bioproducts, technology development challenges, the potential resistance of stakeholders, and the risk of unintended consequences. Conversely, potential threats involve limited stakeholder engagement, conflicting/competing interests, the challenging nature of invasive WH, difficulties associated with managing invasive species, technical complexities, monitoring and evaluation complexities, the impacts of climate change, and regulatory changes. The ongoing management of invasive species and the efficient allocation of resources remain significant challenges.

To capitalize on the strengths and opportunities while mitigating the weaknesses and threats, adopting comprehensive policies, infrastructure investments, and appropriate regulations becomes imperative. These measures are essential to unlock the potential of WH biorefineries, fostering renewable energy production, economic growth, and environmental sustainability in Ethiopia.

5.2. Stakeholders analysis

The potential stakeholders and their intended responsibilities for eradicating invasive WHs through sustainable utilization for a biorefinery in Ethiopia have been identified. The stakeholders include the Government of Ethiopia, the Ministry of Energy and Natural Resources, the Ministry of Environment, Forest and Climate Change, the Ministry of Agriculture and Rural Development, Agricultural Mechanization and Rural Development Research Centers, Ethiopian Biotechnology Institute, Ethiopian Environmental Protection Authority, Ethiopian Institute of Agricultural Research, Ethiopian Sugar Corporation, Ethiopian Electric Power Corporation, private sector companies in the bioenergy and biorefinery industries, NGOs focused on environmental and energy issues, local communities living near WH-infested areas, fishermen, and other water-dependent livelihood groups. The stakeholders have various responsibilities, including providing policy support, regulatory framework, financial resources, incentives, technical expertise, guidance, research, dissemination of information, advocacy for policies, building partnerships, and monitoring and evaluating the impact of technology to ensure sustainable eradication through utilization and control of the weed biomass for value-added products. Table 5 shows the potential stakeholders and their intended responsibilities for WH Biorefinery in Ethiopia.

5.3. Limitations

The quest for sustainable solutions to the environmental and economic issues posed by WH in Ethiopia has led us to propose a comprehensive biorefinery circular economy policy framework. As the study explores these solutions, it is crucial to acknowledge inherent limitations, recognizing that progress comes with challenges. The study's primary limitation is its dependence on data availability and the effectiveness of the circular economy of the WH biorefinery; variations in data quality affect the precision of proposed policies. Additionally, excluding consultation with ongoing regional policy initiatives may overlook emerging policies, highlighting the need for continuous engagement with the evolving policy panorama.

Categorizing biofuels in aggregate without investigating specific intermediary molecules oversimplifies biofuel production and ignores

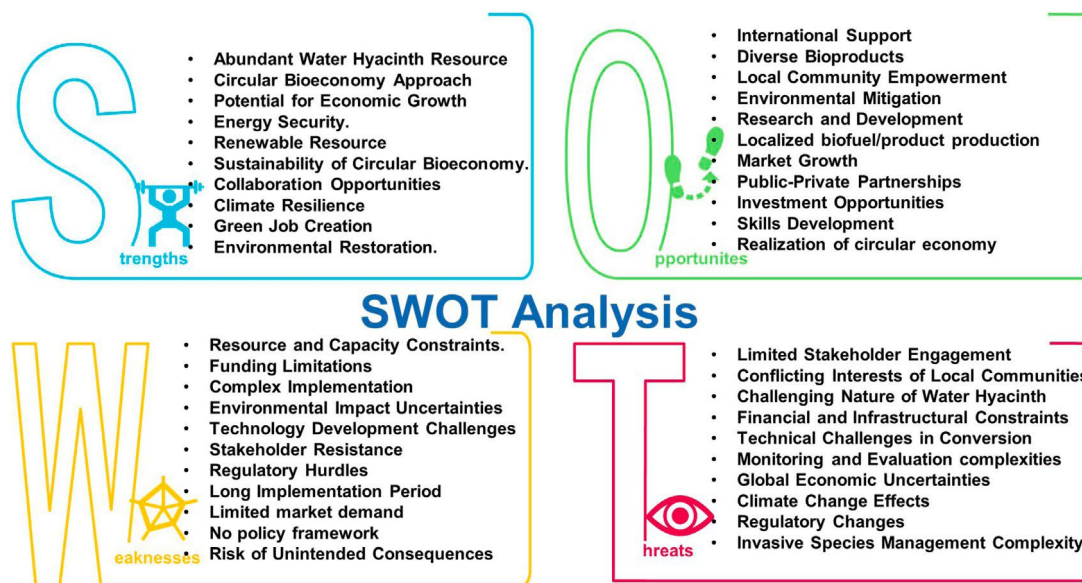


Fig. 5. SWOT analysis.

Table 4

Literature supporting policy framework development.

Category	Reference	Critical review
Policy Framework and Circular Bioeconomy		
Environmental policy: A case for adaptive management	Allen and Garmestani (2015)	This paper advocates for adaptive management within environmental policy, aligning with our framework's need for flexibility in addressing water hyacinth (WH) invasion.
Developing a strategic framework for invasive alien plant management	Foxcroft and McGeoch (2011), May et al. (2022), Djihouessi et al. (2023), Harun et al. (2021)	These sources provide insights into developing strategic frameworks for managing invasive species, which can inform our policy framework for WH.
Strategic policy and management of rivers in South Eastern Australia	Kingsford et al. (2017)	This paper discusses strategic river policy, which could be adapted for WH-infested water bodies in Ethiopia. It emphasizes the importance of policy development and stakeholder collaboration.
Water Hyacinth (WH) Management		
Review on water hyacinth (Eichhornia crassipes)	Jaikumara (2012), Dersseh et al. (2019b)	This review of WH in Ethiopia provides a comprehensive overview of the plant and its management, offering valuable data and insights.
Prospects and constraints of invasive aquatic weeds management	Dechassa and Abate (2020a), Willby (2007)	The source discusses the challenges of managing invasive aquatic weeds, which can inform our framework's potential stumbling blocks.
Survey on water hyacinth management in Ethiopia	Tewabe (2015), Dersseh et al. (2019b), Dechassa and Abate (2020a)	This survey conducted in Ethiopia offers data on WH management and stakeholder involvement, aligning with our stakeholder analysis.
Stakeholder Analysis		
Assessment of stakeholder involvement in the development of water hyacinth management plan	Zikargaa (2022), van den Broek (2019), Zikarga (2018)	The assessment of stakeholder involvement is directly relevant to our stakeholder analysis section. It can provide insights into effective stakeholder engagement.
Challenges and opportunities of water hyacinth management in the water bodies of Ethiopia	Dersseh et al. (2019a), Nega et al. (2021, 2022)	This source can offer valuable data on the challenges and opportunities related to WH management, crucial for our policy recommendations.
Bioeconomy and Biofuels		
Biorefinery in a circular economy approach	Chhandama et al. (2023), Kumar Sarangi et al. (2023), Ganorkar et al. (2021), Kushwaha et al. (2023)	This source discusses biorefineries in the circular economy, aligning with our circular bioeconomy policy framework. It can provide insights into efficient biorefinery strategies.
WH biomass as a sustainable and potentially economical feedstock for bioenergy and bioproducts	Cherwoo et al. (2024), Nega et al. (2021), Wang et al. (2019), Hirphaye et al. (2022), Chhandama et al. (2023)	This source discusses sustainable biomass feedstocks for bioenergy and bioproducts, relevant to our biofuels and biomaterials policy objective.
Environmental Impact and Mitigation		
The green, blue and grey water footprint of crops and derived crop products	Mekonnen and Hoekstra (2011)	This source focuses on water footprints and can inform our water and environmental policy objective, addressing the environmental impacts of WH.
Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment	Jarvie et al. (2013)	This source highlights the importance of managing nutrient pollution, aligning with our nutrient recovery policy objective.

Table 5

Potential stakeholders and their intended responsibilities for WH biorefinery in Ethiopia.

Stakeholder name	Impact	Influence	Importance	Interest	Position
Government of Ethiopia	High	High	High	Environmental protection, energy security, economic development	Key regulators and policymakers.
Local communities living near water-hyacinth infested areas	Low	Moderate	High	Economic benefits, employment opportunities, environmental conservation	Beneficiaries of the project
Fisheries and other water-dependent livelihood groups	High	High	High	Economic benefits, an alternative source of income, improved livelihoods. Utilization of weed biomass	Key partners and beneficiaries
Private sector investors	High	High	High	Profit generation, business opportunities	Key financiers and partners
NGOs and civil society focused on environmental and energy issues	Low	Low	Moderate	Environmental conservation, community development. Advocacy for policies, dissemination of information, building partnerships	Advocates and watchdogs
Academic and research institutions	Low	Low	Moderate	Knowledge generation, innovation, policy development	Advisors and collaborators
International organizations	High	High	High	Environmental protection, sustainable development, poverty reduction	Donors and technical partners
Media	Low	Low	Low	Public awareness, advocacy	Influencers and communicators
Ministry of Energy and Natural Resources	High	High	High	Technical expertise, financial resources	
Ministry of Environment, Forest and Climate Change	High	High	High	Policy support, guidance, monitoring and evaluation	
Ministry of Agriculture and Rural Development	High	High	High	Technical expertise, research, dissemination of information	
Agricultural Mechanization and Rural Development Research Centers	High	High	High	Technical expertise, research, dissemination of information	
Ethiopian Biotechnology Institute	High	High	High	Technical expertise, research, dissemination of information	
Ethiopian Environmental Protection Authority	High	High	High	Policy support, monitoring and evaluation	
Ethiopian Institute of Agricultural Research	High	High	High	Technical expertise, research, dissemination of information	
Ethiopian Electric Power Corporation	High	High	High	Policy support, monitoring and evaluation	
Private sector companies in the bioenergy and biorefinery industry	High	High	High	Financial resources, technical expertise, building partnerships	

crucial nuances for effective policy formation. Despite abundant feedstock availability, the policy framework must consider unique physicochemical or thermochemical characteristics to address the intricate technical aspects of biorefinery operations. The dynamic nature of circular bioeconomy technologies and potential advancements in biorefinery conversion technologies pose another limitation, requiring constant adaptation to emerging trends.

Implementation may face political or social barriers, necessitating adaptive strategies. In conclusion, while contributing significantly to the discourse on WH management, the study underscores the need for a nuanced understanding of limitations. Future research should refine these aspects for a more holistic and adaptive approach to sustainable solutions in the evolving landscape of water hyacinth management.

5.4. Policy framework analysis

The policy framework proposed in this study aims to promote the development and implementation of a biorefinery-based approach for the control and utilization of water WH in Ethiopia. The framework consists of four main policy components: information, economic, cooperative, and regulatory policies.

The information policy component focuses on raising awareness and providing technical knowledge about the biorefinery-based approach to WH control and utilization. It aims to engage stakeholders, including the government, private sector, civil society, and local communities,

in promoting biorefinery-based solutions for WH management. This component involves developing and disseminating educational materials, awareness campaigns, and capacity-building programs to facilitate understanding and adopting the circular bio-economy biorefinery approach.

The economic policy component aims to create market incentives and financing mechanisms to encourage investment in biorefinery-based activities. This component includes the development of policies and programs that promote financial support, such as tax incentives, subsidies, and grants, to stimulate private sector participation in biorefinery-based activities. It also emphasizes the importance of developing markets for WH biomass and its derived products through the establishment of procurement mechanisms and price support mechanisms.

The cooperative policy component emphasizes the importance of collaboration and cooperation among stakeholders to ensure the successful implementation of biorefinery solutions for WH control and utilization. It calls for partnerships between government agencies, private sector entities, and local communities to promote the sustainable management of WH biomass and the development of biorefinery value chains. Cooperative organizations among WH biomass producers are encouraged to facilitate collective action, access to finance, and market opportunities.

The regulatory policy component aims to establish rules and standards for WH biomass management and utilization. It involves the

Table 6

Policy instruments analysis matrix for eradication of invasive WH through sustainable utilization of the weed for a biorefinery.

Policy instrument	Objective	Target stakeholder	Strengths	Weaknesses
Information policy	Raise awareness about the benefits of the biorefinery-based approach to WH control and utilization	Local communities, NGOs, Private sector companies, Government agencies	Low cost, High potential impact, can reach a large audience	May not be sufficient on its own, May require significant resources for implementation
Economic policy	Provide incentives for private sector investment in biorefinery and bioenergy industries	Private sector companies, Government agencies	Can stimulate economic growth, Encourages innovation and entrepreneurship	Can be costly to implement
Cooperative policy	Encourages collaboration and partnerships between stakeholders	All stakeholders	Can build trust and promote shared goals, can facilitate resource sharing and knowledge transfer	May be difficult to implement due to conflicting interests, Requires significant coordination and management
Regulatory policy	Enforce standards and regulations for the sustainable production and processing of WH biomass towards sustainable value-added products	Government agencies, Private sector companies	Can ensure compliance with environmental and social standards, can protect against negative impacts	Can be costly to implement and enforce, May stifle innovation and entrepreneurship

development of a legal framework for the harvesting, transporting, and processing of WH biomass. Additionally, it includes the implementation of environmental regulations to ensure that biorefineries meet minimum standards for air and water quality, waste management, and biodiversity conservation. Developing certification standards for sustainable biorefinery practices is also essential to the regulatory policy component.

By working together, these policy components create a supportive policy environment that facilitates the development and implementation of biorefinery-based solutions for WH control and utilization in Ethiopia. The integration of information, economic, cooperative, and regulatory policies is crucial for the success and sustainability of the biorefinery approach through the Adaptive Management and circular bio-economy policy framework approach discussed in the next sections. Policy Instruments Analysis Matrix for Eradication of Invasive WH through Sustainable Utilization of the Weed for a Biorefinery presented in Table 6.

5.5. Adaptive management approach: Circular bioeconomy policy framework

An adaptive management approach is crucial for effectively addressing the WH invasion. Given the dynamic and complex nature of the problem, a rigid and inflexible strategy would likely be ineffective. Adaptive management involves continuously monitoring the situation, collecting data, and adjusting management strategies accordingly. It promotes a learning-by-doing approach and encourages stakeholder participation, fostering collaboration among government agencies, local communities, and researchers (Allen and Garmestani, 2015; Foxcroft and McGeoch, 2011; Kingsford et al., 2017). By incorporating adaptive management principles, authorities can assess the effectiveness of different interventions, adapt strategies based on real-time feedback, and identify innovative solutions to address the challenges posed by WHs.

Fig. 6 presents the adaptive management approach for the implementation of a policy framework, focusing on five policy objectives: technology adoption, harvesting and pretreatment, biofuels and biomaterials, nutrient recovery, and water and environmental policy objectives. The identified policy instruments, monitoring mechanisms, and implementing bodies will be discussed to highlight the proactive steps taken towards achieving sustainable control and ecological mitigation.

Policy objective 1: technology adoption for biorefinery conversion

The policy objective aims to promote and facilitate the widespread adoption of biorefinery conversion technologies specific to WH biomass. Policy measures include developing comprehensive guidelines, establishing a regulatory framework, tax reduction mechanisms, and investment in research and capacity building. These measures ensure

coherence with the stakeholder collaboration, fostering an enabling environment for technology adoption and sustainable energy practices.

Policy objective 2: harvesting and pretreatment

Efficient biomass harvesting and pretreatment practices are essential for sustainable control and environmental mitigation. The policy framework emphasizes the establishment of regulatory frameworks, financial incentives, supportive policies, and guidelines. These instruments promote sustainable harvesting practices, reduce environmental impacts, and encourage stakeholder collaboration. Public awareness campaigns are crucial in educating stakeholders about the benefits of sustainable practices.

Policy objective 3: biofuels and biomaterials

The utilization of WH biomass for bioenergy production and the development of bioproducts is another policy objective. The framework emphasizes the establishment of regulatory frameworks, market development, marketing strategies, financial incentives, and supportive policies. These instruments create an enabling environment for adopting and utilizing biorefinery technologies, stimulating market demand, economic growth, and sustainable resource utilization.

Policy objective 4: nutrient recovery

The policy objective focuses on recovering and safely applying nutrients from WH biomass in agriculture. The framework highlights the development of guidelines, treatment of residues, and promotion of sustainable practices, financial incentives, and public awareness campaigns. These instruments encourage sustainable nutrient management, reduce reliance on chemical fertilizers, and contribute to soil fertility and nutrient recycling.

Policy objective 5: water and environmental

This objective aims to ensure effective monitoring, evaluation, and reporting mechanisms to track progress and effectiveness, which will be included in the existing national water and environmental policy. To achieve this, the framework proposes measures such as implementing effective wastewater treatment practices, promoting sustainable agricultural practices to reduce nutrient runoff, and regulating industrial discharge to minimize nutrient pollution. Additionally, the policy advocates for creating water shade management, buffer zones, and wetlands to filter and retain nutrients before they reach water bodies, preventing excessive growth of WH. Robust monitoring mechanisms assess implemented policies' outcomes, impacts, and efficiency. This includes monitoring technology adoption, harvesting practices, market demand, nutrient recovery, and socio-economic and environmental outcomes. The evaluation process enables informed decision-making, policy refinement, and resource allocation to achieve sustainable control, environmental mitigation, and socio-economic development.



Fig. 6. Adaptive management approach and policy framework model for sustainable addressing WH invasion problem.

Adaptive monitoring, evaluation, and reporting mechanisms:

The framework includes robust monitoring, evaluation, and reporting mechanisms to track progress and effectiveness. These mechanisms assess the outcomes, impacts, and efficiency of implemented policies. Monitoring focuses on technology adoption, harvesting practices, market demand, nutrient recovery, and socio-economic and environmental outcomes. Reporting enables informed decision-making, policy refinement, and resource allocation to achieve sustainable control, environmental mitigation, and socio-economic development.

Implementing bodies:

The successful implementation of the policy framework relies on the collaboration of various implementing bodies listed in the stakeholder analysis Section 5.2 Table 5. These include government agencies, research institutions, international donors, ministries, small and micro industries, farmers, and fertilizer industry representatives. Each body plays a specific role in executing policies, coordinating efforts, engaging stakeholders, ensuring effective implementation and sustainable resource management.

Overall, the adaptive management approach and comprehensive policy framework provide a roadmap for addressing the WH invasion and achieving sustainable control in Ethiopia. The framework fosters effective policy implementation by incorporating adaptive management principles, stakeholder collaboration, and integrating four policy objectives. The collaborative efforts of implementing bodies from government agencies, research institutions, ministries, industries, and farmers contribute to sustainable control, environmental mitigation, and socio-economic development. This collaborative approach ensures coordination, knowledge sharing, and stakeholder engagement, leading to a sustainable future for Ethiopia.

5.6. A policy framework: Integrating WH management and biorefinery in the circular bioeconomy

The urgent need for sustainable solutions to address environmental challenges has led to the concept of a circular bioeconomy. This section

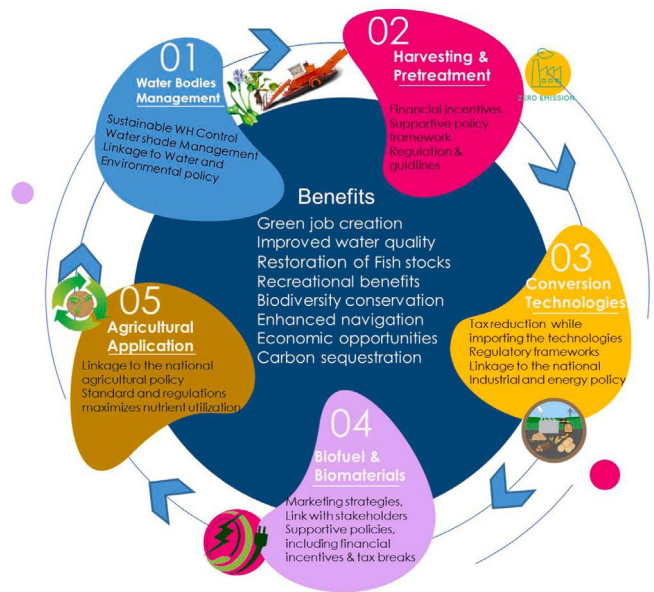


Fig. 7. Circular bioeconomy policy framework for integrated WH management and biorefinery.

explores a comprehensive policy framework that focuses on utilizing WH, an abundant aquatic weed, to promote a sustainable circular bioeconomy. The framework integrates waste management, biofuel production, and environmental restoration while ensuring the efficient utilization of WH biomass in an environmentally sustainable manner.

Integrating WH management and biorefinery practices offers multiple benefits. It addresses the challenge of WH infestation, mitigates environmental impacts, and transforms what was previously considered

waste into a valuable economic resource. This integration reduces dependence on fossil fuels, encourages sustainable practices, and facilitates the transition to a circular economy. The Circular Bioeconomy Policy Framework for Integrated WH Management and Biorefinery (depicted in Fig. 7) highlights the interconnectedness and significance of policies, stakeholder engagement, and technology adoption. It encompasses various components, including water body management, biomass harvesting and pre-treatment, biomass conversion technologies, bioproducts and bioenergy production, and nutrient recovery for agricultural applications.

Water bodies infested with WH and environmental mitigations:

The policy framework prioritizes measures to prevent, monitor, and manage WH infestation in water bodies. Early detection and rapid response systems, water shade management, preventing excessive growth of WH, regular monitoring and assessment of infested areas, and effective control mechanisms are promoted. Collaboration among governmental bodies, research institutions, and local communities is vital for successful implementation. Stakeholder engagement, public awareness campaigns, capacity-building initiatives, and research and development programs are essential in managing WH infestation.

Biomass harvesting and pre-treatment:

Efficient biomass harvesting and pre-treatment are essential for effectively controlling and utilizing WH biomass. Techniques such as drying, composting, and other suitable methodologies are employed to remove excess water and reduce bulk volume. To ensure successful implementation, a supportive policy framework is necessary. This framework should encompass regulations, guidelines, and incentives that promote investments in WH biomass utilization. Financial incentives, such as subsidies or tax breaks, can motivate stakeholders to engage in biomass harvesting and pre-treatment activities.

Biomass conversion technologies:

After pre-treatment, processed WH biomass can undergo various biorefinery conversion technologies to extract valuable compounds. These technologies include anaerobic digestion, fermentation, and thermochemical conversion methods. The policy framework encourages the adoption of tax reduction mechanisms to facilitate the importation of these technologies. A regulatory framework specific to biofuels is crucial, providing guidelines, standards, and regulations governing their production, distribution, and utilization. Aligning biomass conversion technologies with the national energy policy optimizes resource allocation, fosters research and development, and promotes WH biomass integration as a valuable energy resource.

Biofuels and biomaterials:

Extracted compounds from WH biomass present promising opportunities to produce diverse bioproducts. These include biofuels (e.g., bioethanol or biodiesel), biochar, bioplastics, biochemicals, and biofertilizers. A comprehensive policy framework is vital for successful implementation. It should address marketing strategies to promote and commercialize these bioproducts, identify target markets, establish distribution channels, and develop effective communication strategies. Collaboration with stakeholders throughout the value chain, from biomass collection to bioproduct production, ensures an integrated and sustainable approach. Supportive policies, including financial incentives such as tax breaks or subsidies, stimulate investment and incentivize the production of biofuels and other derived byproducts.

Nutrient recovery for agricultural application:

Byproducts obtained during the WH biorefinery process hold significant potential for nutrient recovery. The policy framework advocates for comprehensive measures, including marketing strategies, stakeholder engagement, supportive policies, and financial incentives (e.g., tax breaks) to facilitate successful implementation. Marketing strategies create awareness among farmers and agricultural industries about the benefits of nutrient-rich residues as fertilizers or soil amendments. Collaboration with farmers, agricultural associations, researchers, and policymakers ensures alignment with agricultural practices, maximizes nutrient utilization, and addresses challenges or concerns.

Therefore, the circular bioeconomy policy framework focusing on WH utilization provides a comprehensive approach to promote sustainability, waste management, and economic development. By integrating WH management, biorefinery practices, and the production of bioproducts and bioenergy, this framework addresses the challenges of WH infestation while unlocking economic opportunities. Additionally, it emphasizes the importance of nutrient recovery for agricultural applications (Jarvie et al., 2013). Through stakeholder engagement, supportive policies, and financial incentives, the potential of WH biomass can be harnessed for a sustainable circular bioeconomy, contributing to environmental preservation and economic growth.

6. Results and discussion

The proposed policy framework offers a comprehensive strategy for the control and utilization of invasive WH weed in Ethiopia, aligning with the principles of the circular biorefinery approach. The methodology involved a well-structured process, starting with an extensive literature review to gather insights and best practices. Table 4 presents some literature supporting policy framework development.

Stakeholder consultations with government agencies, local communities, and research institutions were crucial in understanding challenges and opportunities. A SWOT analysis provided a comprehensive assessment of internal and external factors, and an adaptive management approach was integrated, emphasizing continuous monitoring and real-time strategy adjustments (refer Fig. 5). The framework incorporated four key policy instruments—information, economic, cooperative, and regulatory policies—serving specific purposes. Collaboration with international partners and a detailed implementation plan with timelines and priorities were also essential. This methodology ensured that the policy framework was informed by stakeholder input, globally relevant, and designed for flexibility and effectiveness.

The analysis of policy instruments indicates that a combination of information, economic, cooperative, and regulatory policies can effectively address the challenges associated with WH control and utilization (refer to Table 6). The proposed policy framework emphasizes the importance of stakeholder collaboration and involvement in policy development and implementation.

The biorefinery-based circular bioeconomy approach to WH control and utilization has the potential to address multiple challenges in Ethiopia, as revealed through the analysis of relevant literature and stakeholder consultations. A wide range of value-added products can be produced using WH, and the biorefinery framework can be utilized as an effective platform for integrating multiple value chains and enhancing overall resource efficiency. Successful implementation requires effective collaboration among government agencies, private sector stakeholders, and local communities.

The benefits of a circular bioeconomy approach in Ethiopia are substantial, generating new revenue streams and economic opportunities, particularly in rural areas where WH is most prevalent. Biofuel production from invasive WH biomass can address energy insecurity, promote a sustainable circular bioeconomy, and reduce fossil fuel reliance. The framework can also help mitigate the negative environmental impacts

of WH by converting the plant into value-added products and reducing the need for costly and environmentally damaging control measures.

However, successful implementation faces challenges, including limited awareness and understanding of the circular bioeconomy concept, insufficient policy and regulatory frameworks, and inadequate infrastructure and financing. Addressing these challenges requires effective collaboration, targeted capacity-building initiatives, and the development of supportive policy and regulatory frameworks. The biorefinery-based circular bioeconomy approach to WH control and utilization can contribute significantly to Ethiopia's environmental sustainability, energy security, and economic development.

The adaptive management approach within the circular bioeconomy policy framework, illustrated in Fig. 6, is a pivotal aspect of the proposed strategy. This approach recognizes the ever-changing and complex nature of invasive WH infestations and their management. Addressing such a dynamic problem necessitates revising the traditional control and management approach. Therefore, the adaptive management approach focuses on continual monitoring, data collection, and the flexibility to adjust strategies as new information becomes available. It promotes a learning-by-doing philosophy, encouraging the active participation of stakeholders, including government agencies, local communities, and researchers. By incorporating adaptive management principles, authorities can evaluate the effectiveness of different interventions, adapt their strategies based on real-time feedback, and identify innovative solutions to address the challenges posed by invasive WH weed. This approach ensures that the policy framework remains agile and responsive to evolving circumstances, making it a robust and sustainable strategy for tackling invasive WH infestations.

In integrating WH management and biorefinery into the Circular Bioeconomy Policy Framework illustrated in Fig. 7, the circular bioeconomy policy framework comes into focus, providing a comprehensive strategy for addressing the invasive WH issue in Ethiopia. This framework of a circular bioeconomy is designed to harmoniously integrate the management of WH with biorefinery practices, effectively transforming an environmental problem into a valuable resource. The framework consists of various interrelated components, including strategies for water body management, efficient biomass harvesting and pretreatment, adoption of biomass conversion technologies, and developing a bioproducts and bioenergy sector. Stakeholder engagement, public awareness campaigns, and collaborative research and development efforts are pivotal in successfully executing this framework.

The circular bioeconomy policy framework presents a multifaceted approach to WH infestation control, mitigating environmental impacts, and harnessing economic opportunities. By integrating these key components, the framework effectively reduces reliance on fossil fuels, fosters sustainable practices, and propels the transition towards a circular economy. This approach addresses the various dimensions of the invasive WH challenge in Ethiopia, ensuring that the infestation is not merely controlled but converted into a valuable resource.

6.1. Findings from stakeholder consultations

The analysis of findings from the stakeholder consultations reveals significant insights and recommendations derived from comprehensive discussions on WH management and utilization. The findings encompass various aspects, including water shade management to control WH from the source, the economic considerations of utilization versus eradication, and the potential utilization of WH as animal feed, particularly for fish and livestock. Additionally, the analysis examines the cost implications, nutritional profile, oregano Chloro Phosphate accumulation in WH, and amino acid profile, among other factors.

One significant observation from the stakeholder consultations is that many countries face the challenge of not only formulating policies but also implementing them effectively. Acknowledging this, it is understood that policy development and implementation constitute a long-term process, requiring practical strategies and concerted efforts.

In light of this understanding, the stakeholders are eager to contribute to the group in any capacity.

The analysis further highlights the challenges associated with WH proliferation, including rapid growth, negative impacts on aquatic ecosystems, and potential threats to biodiversity. To address these challenges, the policy framework should prioritize early detection, integrated management approaches, and active engagement of local communities.

Stakeholders have underscored WH utilization's significant environmental, economic, and social benefits. These include mitigating invasive species, creating employment opportunities, generating income, and empowering local communities. While maximizing these benefits, ensuring sustainable harvesting practices and minimizing any unintended negative consequences on the environment and socioeconomic aspects is crucial.

Supportive mechanisms, such as financial incentives, grants, public-private partnerships, and knowledge-sharing platforms, are essential in facilitating the establishment of biorefineries for WH utilization. Additionally, research and development are crucial in advancing technologies and processes for efficient WH control and conversion.

Overcoming implementation barriers requires institutional coordination, regulatory compliance, and capacity building. Stakeholder roles and responsibilities need to be clearly defined, with active participation from government agencies, local communities, industry stakeholders, research institutions, and non-governmental organizations in the policy implementation process.

The findings also underscore the importance of inclusivity, equitable distribution of benefits, and learning from successful case studies and best practices. Financial mechanisms and diverse funding sources are explored to support implementation efforts and the establishment of biorefineries. Monitoring, evaluation, and adaptive management are recognized as crucial elements in ensuring the long-term effectiveness and relevance of the policy framework.

Overall, the stakeholder consultations have provided valuable insights into WH management and utilization, offering a foundation for policy development and implementation strategies in this complex domain.

6.2. Implementation plan: A theory of change perspective

The theory of change for policy framework, as illustrated in Fig. 1, provides a structured and strategic approach to prioritizing and implementing the formulated policies within specified timelines. In the short term, the primary emphasis lies in augmenting awareness and comprehension of the comprehensive policy frameworks through active stakeholder engagement and collaborative endeavors. Simultaneously, concerted efforts are directed towards fortifying technical expertise and capacity building, setting the stage for a robust policy foundation.

As we transition into the medium term (3–5 years), the policy framework is anticipated to evolve significantly. This phase foresees a substantial increase in utilizing invasive WH biomass, resulting in notable annual biofuel production and various value-added products. Integrating the policy framework with national energy policy, economic development strategies, and environmental policies will be pivotal. Consequently, this surge in invasive WH biomass utilization is expected to yield a marked reduction in WH proliferation over the medium term. The consequential benefits will extend to the local communities, driven by the increase in creation of green jobs and the value addition stemming from WH biomass utilization as a biorefinery feedstock.

Looking forward to the long term (spanning 10 to 20 years), the policy framework is poised to establish sustainable invasive WH management across Ethiopia's water bodies. This phase will witness a substantial diversification of the national energy mix, strongly emphasizing generating renewable energy from distributed sources. The implications are far-reaching, as this transition is expected to catalyze national economic development and be a potent driver for poverty reduction. The substantial sale of bioproducts in foreign markets is anticipated to yield significant annual revenue, solidifying Ethiopia's position in the renewable energy and bioproducts industry.

6.3. Potential stumbling blocks

The comprehensive policy framework for the utilization of invasive WH in Ethiopia presents an exciting opportunity for biofuel generation and environmental mitigation. However, it is essential to acknowledge the potential stumbling blocks that could hinder the successful implementation of this framework. Identifying and addressing these challenges is crucial for ensuring the effective utilization of WH biomass and realizing the associated economic, social, and environmental benefits.

Limited stakeholder engagement:

Active collaboration among various stakeholders is crucial for the success of the policy framework on circular bioeconomy and weed biomass utilization. Limited awareness poses a challenge, especially regarding the benefits and potential of using weed biomass for biofuel. Targeted capacity-building initiatives, such as workshops and seminars, should be implemented to overcome this. These efforts aim to educate stakeholders and address concerns about weed infestation. Empowering local communities is essential for the effective implementation of the policy framework.

Conflicting interests of local communities:

Ethiopian communities residing around water bodies like Lake Tana, Lake Zuway, and Awash River greatly rely on these resources for their daily activities, including fish production, irrigation, hydropower generation, and freshwater supply. Due to a limited understanding of the exponential growth nature of WH, some communities might prioritize the complete eradication of the weed, believing it to be the best solution to protect their livelihoods. However, given the invasive nature of WH and its ability to rebound rapidly, complete eradication is not practically feasible. Educating these communities about the benefits of controlled utilization of WH is essential. Efforts should be made to inform them about the limitations of complete eradication and the positive impacts of controlled utilization, such as generating income and reducing the adverse effects of uncontrolled growth.

Challenging nature of WH:

The invasive Water Hyacinth (WH) weed presents a formidable challenge due to its aggressive nature. Once established, it out-competes native vegetation, proving challenging to control or eliminate. With both sexual and vegetative reproduction, its population proliferates. A single inflorescence yields up to 3000 seeds, viable for over two decades, leading to potential resurgences. WH can double its population every 5 to 13 days through vegetative reproduction. Lake Tana, for instance, faced a significant impact, with around 50,000 hectares affected along approximately 130 kilometers of its northern shore in 2015 (Nega et al., 2022). Despite national efforts, internal conflicts in Ethiopia since 2018 have diverted attention from weed control, potentially worsening the situation. Given these challenges, the most innovative approach is controlled utilization for effective WH population management.

Financial and infrastructural constraints:

Implementing the policy framework requires substantial financial investments for establishing biorefineries and the necessary infrastructure for WH biomass utilization. However, access to financing mechanisms may be limited, and inadequate infrastructure could further hinder progress. Financial incentives, grants, and public-private partnerships should be explored to address these obstacles to attract investments in WH biofuel projects. Specialized financing mechanisms and credit facilities can also support small-scale entrepreneurs and farmers involved in WH removal, harvesting, and processing activities, making the endeavor economically viable.

Technical challenges in conversion. Converting WH biomass into value-added products for biofuel generation poses technical challenges. Efficient and cost-effective conversion technologies need to be developed. Standardized processes for harvesting, storing, and transporting WH biomass are necessary to ensure smooth and effective utilization. Collaborative research and development initiatives, including partnerships with national and international research organizations, are crucial in overcoming these technical hurdles. The involvement of academia, industry stakeholders, and government agencies is vital for advancing the technological aspects of WH biomass utilization.

Monitoring and evaluation:

Monitoring and evaluation are essential to ensure the effectiveness and sustainability of WH management and biofuel generation initiatives. Establishing comprehensive data collection systems and robust monitoring frameworks might be challenging, especially in remote areas with prevalent WH infestations. Nevertheless, developing a monitoring and evaluation framework that tracks crucial indicators such as WH infestation levels, biofuel production volumes, employment generation, and environmental impacts is vital. Regular assessments based on these indicators will provide valuable insights, enabling policymakers to make informed decisions and adjust strategies accordingly.

Therefore, overcoming these challenges requires collaborative efforts, capacity building, targeted financing mechanisms, and continuous monitoring and evaluation. By addressing these stumbling blocks, Ethiopia can unlock the opportunities presented by invasive WH and harness its potential for the sustainable development of a circular bioeconomy.

6.4. Support from the international community

Ethiopia's effective control and use of invasive WH rely on solid support from the international community. Given Ethiopia's role as the water tower of East Africa and the presence of infested water bodies with transboundary significance, collaborating with intercontinental and regional efforts is vital to boost their initiatives. Partnering with international research organizations, academic institutions, and experts facilitates the development of efficient conversion technologies and best practices for utilizing WH biomass effectively. Financial support through grants and investments is crucial for establishing biorefineries and related infrastructure, promoting sustainable growth in Ethiopia's biofuel industry. Moreover, involving other Nile basin countries in circular bioeconomy biorefinery-based businesses can lead to collective remedial actions.

International organizations are pivotal in policy development, ensuring alignment with global sustainability goals. Capacity-building initiatives are essential for enhancing the skills and knowledge of local stakeholders. Advocacy efforts raise awareness about WH biomass utilization and circular bioeconomy approaches, fostering increased international collaboration. Ultimately, the successful control and utilization of WH biomass in Ethiopia depend on cooperation between national and international partners, leading to sustainable development, energy security, and environmental protection in the region.

7. Conclusion and policy recommendations

The study shows the potential of WH for biofuel generation and environmental mitigation in Ethiopia, aiming to provide essential information to policymakers, investors, and stakeholders for the advancement of the biofuel industry. The circular bioeconomy policy framework offers a promising solution to the WH invasion, promoting environmental sustainability, energy security, and economic development. This innovative approach recognizes the potential of WH, a problematic invader of aquatic ecosystems, as a valuable resource for biofuel production and a wide range of value-added products. By addressing a comprehensive set of policy objectives, the framework

takes a holistic approach to tackle not only the ecological and economic challenges posed by WH but also to harness the full potential of this invasive weed.

WH biofuel generation presents an opportunity to mitigate the threats posed by this invasive weed. The advantages are manifold: economic empowerment of local communities, increased energy security, promotion of a sustainable bioeconomy, and reduced reliance on imported/fossil fuels. Furthermore, the framework emphasizes how WH utilization can significantly reduce the negative environmental impacts associated with traditional control measures that are often costly and environmentally damaging.

However, the path to successful implementation has its challenges. Limited awareness of the circular bioeconomy concept, inadequate policy and regulatory frameworks, lack of infrastructure and financing, technical difficulties in biomass conversion, and the need for robust monitoring and evaluation systems are potential stumbling blocks.

To ensure the effective utilization of WH biomass and the realization of the associated economic, social, and environmental benefits, the policy recommendations on how the policy framework helps are essential:

1. *Formulating and implementing a dedicated national policy or strategy for WH management and utilization must address the diverse challenges posed by WH infestations.* Collaborating with relevant stakeholders, including government agencies, environmental organizations, researchers, and affected communities, becomes essential to ensure a well-rounded and inclusive approach.
2. *It is critical to allocate sufficient funding for research and development initiatives related to WH management and utilization.* Funding support could be directed towards adopting and optimizing biorefinery technologies for converting WH biomass into value-added products. Additionally, financial support for conducting research on the environmental impacts of control measures and identifying sustainable utilization practices could enhance the effectiveness of future policies.
3. *Financial incentives such as tax breaks, grants, or low-interest loans are needed to attract investments in WH biofuel projects and circular bioeconomy ventures.* Encouraging public-private partnerships might be beneficial to leverage private sector expertise and resources while ensuring effective oversight by government agencies. Such collaborations can accelerate the development and implementation of innovative solutions to combat WH infestations.
4. *Small-scale entrepreneurs and farmers must actively participate in WH removal and processing activities.* Empowering these individuals and local communities is crucial for strengthening the effectiveness of resource utilization efforts at the grassroots level. By actively involving these stakeholders, policymakers can promote a sense of ownership and responsibility in managing WH issues within their communities.
5. *Wide-reaching awareness campaigns that target the public, policymakers, and industries are essential to the success of the policy framework.* By effectively communicating the significance of addressing the WH problem and highlighting the potential benefits of utilizing the WH weed as a resource, policymakers can generate widespread support and participation. Engaging stakeholders through these awareness campaigns fosters buy-in and enhances the overall effectiveness of the policy framework.
6. *Adaptive monitoring and evaluation frameworks are needed to assess WH management initiatives' progress and impact continuously.* By using well-defined indicators to measure the reduction of WH infestations, environmental impacts, and socio-economic benefits, policymakers can make data-driven decisions. Regular evaluations enable policymakers to make necessary adjustments to optimize the policy framework's outcomes and implementation reforms of the adaptive management framework, ensuring its ongoing effectiveness and relevance.

7. *Given the potential cross-border impact of WH infestations, collaboration should be considered with neighboring countries in the Nile basin facing similar challenges.* Establishing regional legislation and fostering interagency cooperation can enhance collective efforts in combating the invasive WH menace. This approach recognizes that water bodies and ecosystems often extend beyond national boundaries and underscores the importance of regional cooperation in addressing shared environmental challenges.
8. *Common challenges in East Africa and international cooperation and partnerships to address WH challenges.* Engaging with other countries, organizations, and institutions would provide access to valuable expertise, resources, and funding to support Ethiopia's efforts in combating WH infestations. Collaborating on a global scale would promote mutual learning and exchange, benefiting all parties involved and enhancing the effectiveness of solutions for long-term environmental and socio-economic sustainability in Ethiopia.

The successful realization of the policy framework can lead Ethiopia towards a circular bioeconomy that harnesses the potential of invasive WH for sustainable development, environmental preservation, and economic growth. Through collaborative efforts, international support, and a commitment to overcoming challenges, this framework can serve as a model for other countries facing similar challenges, supporting the global transition towards a circular bioeconomy aligned with global sustainable development goals.

CRediT authorship contribution statement

Derese T. Nega: Conceptualization, Formal analysis, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Venkata Ramayya Ancha:** Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Flavio Maenti:** Conceptualization, Formal analysis, Investigation, Resources, Supervision, Validation, Visualization, Writing – review & editing. **Zafar Adeel:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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