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Weed valorization: Harnessing the potential of weeds for sustainable development

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Abstract

Invasive weeds pose significant threats to environmental sustainability and local economies due to their rapid spread and competitive dominance over native vegetation. Failure to manage these weeds can disrupt biodiversity, reduce crop yields and impact agricultural livelihoods. Addressing the challenges posed by these weeds requires a comprehensive and multidisciplinary approach for their management. Despite their detrimental impacts, weeds possess considerable potential as renewable biomass resource for alternative energy production. Their rapid growth, high biomass yield and ability to adapt in diverse environmental conditions make them suitable feedstocks for sustainable energy generation. Therefore, the utilization of invasive weeds for biofuel production offers a dual benefit by contributing to effective weed management and simultaneously supporting energy production.

Keywords: Biodiversity, biofuel, invasive weeds, renewable, sustainable

Introduction

The growing demand for fuel in both urban and rural areas, particularly for transportation and industrial applications, has raised concerns regarding the environmental impacts associated with fossil fuel consumption, rising crude oil prices and the depletion of fossil fuel resources. Therefore, in order to satisfy the needs of society through sources that are renewable, researchers are presently focusing on sustainable alternatives to conventional fossil fuels. Currently, renewable sources contribute 4.7% of the total liquid transport fuel produced (Saoud, 2018) [20]. Biomaterials including cellulosic materials, sugary crops, starchy grains, oil crops, and organic wastes are used to make biofuels. Biofuels are broadly classified into two major categories: biodiesel and bioethanol. Wheat, sorghum, corn, beetroot, and sugarcane are the primary ingredients used to make bio-ethanol, whereas biodiesel is commonly derived from oil-bearing seeds including sunflower, palm and rapeseed (Pandiyani *et al.*, 2019) [14]. Fuels made from sources including sugar, starch, vegetable oils and animal fats are referred to as first generation biofuels. Despite their potential as renewable sources, first generation biofuels have raised concerns about environmental sustainability and carbon balances, which restricts the first generation biofuel production. A major limitation associated with these biofuels is the food-versus-fuel debate, as the increased use of food crops for fuel production may contribute to rising food prices and threaten food security (Kim and Dale, 2004; Laursen, 2005) [8, 10]. In contrast, second generation biofuels are produced from lignocellulosic biomass and other non-food crops, which are considered either carbon neutral or carbon negative in terms of their impact on atmospheric CO₂ levels. Lignocellulosic materials are regarded as a significant renewable feedstock for bioethanol production without posing a threat to the supply of food or animal feed (Demirbaş, 2003) [4].

Lignocellulosic materials are the most abundant renewable organic resources available worldwide with an estimated annual production of nearly 200 billion tonnes. These can be easily converted into bioethanol and other value-added products. Woody substrates like hardwood (e.g. aspen and birch) and softwoods (e.g. pine and spruce), agricultural residues like sugarcane bagasse, corn stover, wheat straw and paddy straw, as well as dedicated energy crops such as *Miscanthus*, switch grass; weeds (*Parthenium hysterophorus*, *Eicchornia crassipes*, *Hydrilla*,

Lanta Eicchornia crassipes, *Lantana camara*, etc.), and municipal solid waste (kitchen and food waste) are considered as important lignocellulosic substrates (Chandel and Singh, 2011)^[3]. This review focuses on the potential of weedy biomass, including terrestrial and aquatic weeds, as a sustainable feedstock for biofuel production. Management of weeds has become a major global challenge due to the rapid proliferation and invasive nature of these plants. However, due to their high lignocellulosic content weeds have gained considerable attention as an alternative and cost-effective substrate for biofuel production. Weeds are generally the unwanted plants that grow alongside cultivated crops in agricultural fields, wetlands, and

marshy areas.

They adversely affect agricultural and forest productivity by competing with crops for nutrients, water, light as well as space. Furthermore, invasive weeds threaten stability of the ecosystem by disrupting native biodiversity and negatively affecting endangering native plants and animals. Despite these negative effects that weeds have on the environment, their increased biomass yield, rapid growth rate and adaptability to diverse environmental conditions make them promising feedstocks for renewable energy production. Weedy biomass can be converted into various forms of biofuels through biochemical and thermochemical conversion strategies (Fig 1).

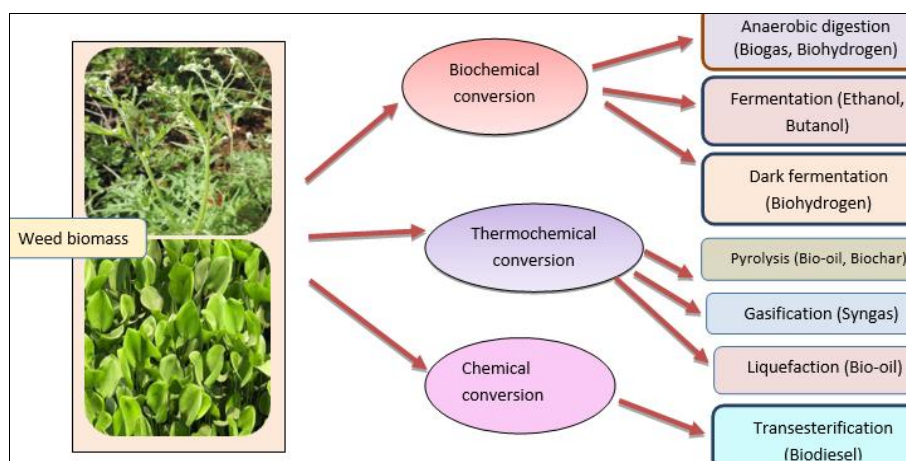


Fig 1: Processes used to convert weed biomass to usable energy

Several studies have demonstrated the effectiveness of processes such as anaerobic digestion, incineration, pyrolysis, gasification, and oxidation for obtaining enhanced biofuel yields (Kataki and Kataki, 2022)^[7]. Thermochemical conversion processes for converting biomass into biofuel are pyrolysis, liquefaction, combustion, and gasification which lead to the production of bioethanol, biodiesel, bio-oil, syngas, and biohydrogen (Ong *et al.*, 2019)^[13]. Prior to biofuel production, lignocellulosic weedy biomass requires pretreatment to disrupt the complex structure of cellulose, hemicellulose and lignin. The pretreatment process enhances the accessibility of fermentable sugars and improves the efficiency of conversion of pretreated biomass to biofuels.

Terrestrial weeds

Terrestrial weeds are often called as threatening weeds because of their adverse interactions with the surrounding plant species. These weeds release various biochemical compounds, including allelochemicals and phenolic compounds that inhibit the germination and growth of other plants. Some terrestrial weeds also pose serious health hazards to humans by causing severe allergic reactions. Numerous studies have investigated physical, conventional, and biological approaches for weed management and many of these methods are associated with limitations such as high cost, low efficiency and environmental concerns, with biological methods being comparatively more ecofriendly (Alam *et al.*, 2021)^[1]. Among the commonly occurring terrestrial weeds, *Amranthus retroflexus* and *Parthenium hysterophorus* have gained attention as potential feedstocks for biofuel production.

P. hysterophorus commonly known as congress grass, is a toxic and invasive herbaceous weed with no significant commercial value. It has many negative effects on biodiversity and agriculture and ecosystem stability. The uncontrolled growth of *P. hysterophorus* in agricultural fields significantly

reduces the productivity of crops such as sugarcane, cotton, fodder crops, and vegetable by competing for essential resources including water, soil nutrients, space and sunlight. Due to its rapid rate of seed production and germination, it has the capacity to spread quickly over large geographical areas. This weed produces pollen into the air, which poses serious health issues to humans such as hay fever, allergies, asthma, dermatitis, pneumonia, and diarrhoea. The plant is highly adaptable and can survive under extreme and diverse environmental conditions and can grow in a variety of soil type, producing flowers and seeds throughout the year even under unfavorable conditions making it a global concern (Patel, 2011)^[15]. Despite its harmful effects, *P. hysterophorus* has considerable potential as a bioenergy feedstock for the production of bioethanol, compost and biogas. The plant contains approximately 10.44% lignin and 53.63% hemicellulose, making it a desirable feedstock for the synthesis of bioethanol (Tavva *et al.*, 2016)^[22]. Compared to other biomass, *Parthenium hysterophorus* has a fairly high lignin content ranging from 18–23% which can hinder methane production during anaerobic digestion by reducing biodegradability and prolonging the hydrolysis stage which is one of the quick stages of anaerobic digestion. Pretreatment is must to overcome these obstacles, and it also improves the efficiency of anaerobic digestion. Various pretreatment techniques have been explored to degrade lignin and improve substrate digestibility. Saha *et al.* (2021)^[19] employed electrohydrolysis pretreatment of *P. hysterophorus* to accelerate hydrolysis step and improve biogas production. Compositional analysis after pretreatment revealed an increase in soluble lignin and cellulose and decrease in hemicellulose concentration. Cumulative methane production increased significantly in the pretreated sample as compared to untreated one demonstrating the effectiveness of pretreatment in improving anaerobic digestion process.

Amaranthus retroflexus commonly referred to as redroot pigweed, is considered a promising second-generation lignocellulosic biomass feedstock for biofuel production. This plant belongs to the fast-growing C4 herbaceous plant family, which comprises approximately 60–70 species. This is a universal species that can survive diverse environmental conditions including cryolitic zones. The plant can grow to a height of 1.5 to 3 meters while requiring comparatively low amounts of water and fertilizer enabling higher biomass production with low agricultural inputs (Madadi *et al.*, 2021) ^[11]. Karaeva *et al.* (2023) ^[6] investigated the pyrolysis of *Amaranthus retroflexus* using a laboratory scale furnace for the production of biofuel. Drying, devolatilization (release of volatile compounds), and carbonization are the three main stages employed for pyrolysis of lignocellulosic material. Three

products (gas, bio-oil, and biochar) were produced as a result of the pyrolysis procedure in a laboratory environment at a temperature of 550 °C. Among these products, Bio-oil or pyrolysis liquid, dominates the composition of pyrolysis products.

The yield of pyrolysis products is influenced by the relative concentration of lignin, cellulose and hemicellulose present in the biomass (Fig 2). Biomass feedstocks with higher cellulose and hemicellulose content generally favor the production of bio-oil, whereas while biochar is produced when there is a high concentration of lignin. The increased yield of biochar in lignin-rich biomass is primarily due to the structural complexity and high thermal resistance of lignin that make it more difficult to decompose during the pyrolysis process (Hoang *et al.*, 2021) ^[5].

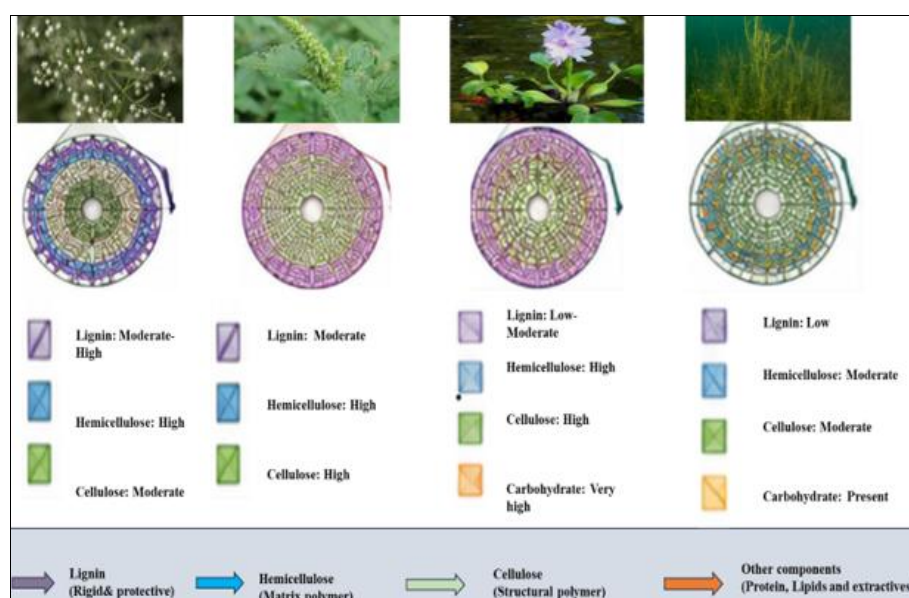


Fig 2: Structural diversity of lignocellulosic weed biomass

Aquatic weeds

Aquatic weeds represent a global environmental challenge because of their rapid proliferation and uncontrolled growth in water bodies. Considerable financial resources and labour are required for their management, removal and disposal from the aquatic systems. However, these invasive aquatic weeds can be useful and profitable when utilised as a potential resource. Aquatic weed has the potential to be used as a feedstock in the production of biofuels due to its high carbohydrate and protein content. The lignin and sugar components of aquatic weeds can be used in thermochemical processes to produce bio-oil, combustible gases, and thermal energy. The sugar component might undergo fermentation to yield bioethanol, biomethanol and biobutanol. It could be possible to make biodiesel using the aquatic lipid component. Moreover, biological processes can facilitate the production of bio-methane and bio-hydrogen from the aquatic weed biomass. The degradation of aquatic weed biomass could be accelerated by process intensification (such as sonication and microwave) during pretreatment processes (Alam *et al.*, 2021) ^[11]. Among the various aquatic weeds, *Hydrilla verticillata* and *Eichhornia crassipes* are the most widely recognized as promising feedstocks for biofuel production.

Eichhornia crassipes commonly known as water hyacinth, is regarded as one of the most problematic aquatic weeds due to its ability to form dense and impenetrable floating mats on the water. It is a free-floating aquatic macrophyte that can be annual

or perennial. Native to Brazil, *Eichhornia crassipes* was introduced into India as an ornamental plant in West Bengal during beginning of the 20th century. Since its introduction, the species has spread extensively and has affected the water surfaces. The plant reproduces through both vegetative propagation as well as sexual reproduction via seeds. Around 5000 thousand seeds can be produced by a single water hyacinth plant contributing significantly to its rapid spread and invasiveness. The uncontrolled proliferation of *Eichhornia crassipes* poses a serious threat to aquatic ecosystems and biodiversity. The dense floating mats reduce light penetration, displace indigenous flora and restrict the access to the water for birds and other wildlife. Furthermore, the accumulation of plant biomass and its decomposition hinder oxygen transfer within the aquatic systems, creating hypoxic conditions leading to mortality of fishes and other aquatic fauna (Bote *et al.*, 2020) ^[2]. *Eichhornia crassipes* is considered a potential lignocellulosic feedstock with a high hemicellulosic content. Its utilization for biofuel production seems to be a feasible option for both aquatic weed management and mitigation of environmental pollution and the energy crisis (Sindhu *et al.*, 2017) ^[21]. Photong and Wongthanate (2020) ^[17] investigated the production of biofuel from water hyacinth (*Eichhornia crassipes*) in combination with cassava starch sediment through biological and physical conversion processes. Anaerobic digestion was used in the biological conversion process to produce biomethane. The

optimal conditions for biomethane production included a water hyacinth to cassava starch sediment ratio 25:75, an initial pH of 7.5, a thermophilic temperature (55 ± 2°C), and a carbon-to-nitrogen (C/N) ratio of 30:1. Under these optimized conditions, the maximum chemical oxygen demand (COD) removal efficiency achieved was 87.40%, and the biomethane production was 436.82 mL CH₄ g⁻¹ COD. In addition to biological conversion, physical conversion processes such as bio-briquetting have also been explored for energy generation from aquatic weed biomass. Photong and Wongthanate (2020)^[17] evaluated gross electricity production from bio-briquettes prepared using different ratios (10:90, 20:80, 30:70, 40:60, and 50:50) of *Eichhornia crassipes* and cassava starch sediment, respectively which yielded gross electricity outputs of 1.52, 1.50, 1.47, 1.45, and 1.42 kWh, respectively.

Hydrilla verticillata is a submerged aquatic plant widely recognized for its high nutrient adsorption capacity and adaptability, making it useful for remediation of polluted water

bodies. (Mishra *et al.*, 2014)^[12]. However, under favorable environmental conditions, particularly in the presence of direct sunlight, the plant proliferates rapidly and spread across aquatic ecosystems. Excessive growth of *Hydrilla verticillata* can disrupt ecological balance and the decomposition of untreated biomass may release pollutants into water systems aggravating the environmental degradation. Therefore, effective management and utilization of the biomass is essential. If this plant is successfully included into the bio-energy processes, it may not only offer a sustainable fuel source but also contribute to keep the ecosystem in balance. Promdee *et al.* (2021)^[18] investigated the conversion of *Hydrilla verticillata* into bio-oil and charcoal using continuous pyrolysis technique. The pyrolysis process was conducted at a controlled temperature ranging from 300 to 700 °C. The highest bio-oil yield (41.25%) was achieved at 700 °C, whereas the maximum charcoal yield (44.98%) was obtained at 300 °C. These findings demonstrate the impact of temperature variation on product distribution.

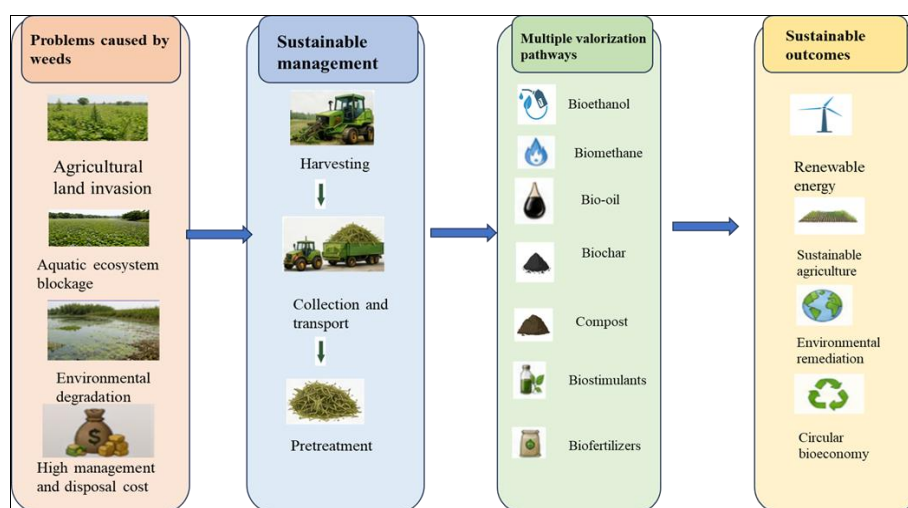


Fig 3: Integrated management and valorization of weedy biomass

Through integrated management of invasive weeds, the environmental burden can be reduced by converting their biomass into useful products (Patil *et al.*, 2026)^[16]. Biochemical and thermochemical routes are used to process the weedy biomass after collection and pretreatment to produce bioethanol, biomethane, bio-oil, biochar, compost, biofertilizer, and biostimulants to support waste valorisation and promote circular bioeconomy goals (Klavins *et al.*, 2024)^[9].

Conclusion

Bioconversion is an effective and ecofriendly approach for management of weeds. Instead of treating weeds as waste, this approach converts them into useful products such as compost, biogas, vermicompost, biofertilizers etc. This method helps to reduce weeds infestation, improves soil fertility and recycles the nutrients. By transforming weed biomass into valuable resources, bioconversion process supports sustainable agriculture, reduces environmental pollution. However, it is advised that weeds should be removed for use a value-added products to reduce weed seed dispersal.

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