# Sustainable Utilization of Invasive Alien Plant Species for Bioenergy and Fodder: A Narrative Review with Insights from Paper Mulberry

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***Abstract***

*Invasive alien plant species (IAPS) present environmental and socioeconomic issues throughout the Globe, but many also provide unexplored possibilities for sustainable resource use. This study examines the dual purpose of Broussonetia papyrifera (Paper Mulberry), a very invasive plant in South Asia, as a biomass source for bioenergy and as unconventional livestock feed. A narrative review approach combined current literature with contextual information from recent fieldwork under review in Pakistan. The results suggest that Paper Mulberry has desirable traits for producing briquettes and bioethanol. Its leaves are nutritionally similar to traditional forages used in small livestock systems. The review also emphasizes the implications of employing IAPS concerning the Sustainable Development Goals (SDGs), particularly 7, 13, and 15. Despite the potential, there are still obstacles to technological readiness, awareness, and policy alignment. The study concludes that the sustainable use of IAPS, such as Paper Mulberry, can aid in ecological restoration, rural development, and clean energy transitions with careful planning and collaboration across sectors.*

**Keywords**: Paper Mulberry, Invasive Species, Biomass Briquette, Fodder Potential.

## Introduction

Due to the increase in the world's population and the industrialization of developing nations, humanity's energy needs have reached unprecedented heights. Nonetheless, the pace at which fossil fuels are used is much higher than the rate at which they are created, which takes millions of years (Yang et al., 2024). Over the last few centuries, the planet's average temperature has risen

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by about 1.2 °C. As a result, climate change has posed several threats to both human and natural systems, such as rising sea levels, species extinction, extreme weather, and food and water scarcity (He et al., 2022). The constant rise in the use of renewable energy has been influenced by factors such as the desire to slow down climate change, the increasing global demand for electricity, the unpredictability of the petroleum market, and the lower environmental impact of renewable fuels. (Latterini et al., 2022) The Paris Agreement, which was started in 2015, aims to limit global temperatures to 2°C above preindustrial levels and strives to keep the increase to 1.5 °C to lessen the adverse effects of greenhouse gas emissions on the environment (Khan et al., 2021). The United Nations Sustainable Development Summit approved 17 SDGs to address pressing societal issues like hunger, poverty, health and wellbeing, gender equality, and climate action by 2030. SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 15 (Life on Land) highlight the critical need for sustainable management of terrestrial ecosystems and the development of clean energy (Park et al., 2023). The SDGs are a crucial worldwide initiative to foster growth and create a better future (Sorooshian, 2024).

To attain sustainable development, nations are actively exploring and using renewable resources (natural resources that replenish themselves on a timescale acceptable to humans), such as solar energy, wind energy, hydropower, and biomass, to lessen environmental harm and dependence on fossil fuels. Biomass is the fourth-largest energy source after crude oil, coal, and natural gas because it is the only renewable energy source consistently creating liquid fuels and chemical feedstocks for transportation. Forest leftovers (hardwood, softwood, and grasses), agricultural waste (straw, husks, and stalks), aquatic biomass (algae), and a variety of organic waste are among the biomass resources that are found all over the world. These resources have the advantages of being environmentally benign, widely applicable, and abundant (He et al., 2022; Yang et al., 2024; UNECE, 2016; Khan et al., 2022; Mignogna et al., 2024).

Biomass is regarded as a viable option for addressing these energy concerns in developing nations like Pakistan. Pakistan and other developing countries are lagging in adopting the necessary practices and procedures to utilize biomass as a viable renewable energy source. Due to restricted access to fossil fuels, most of Pakistan's rural population uses wood, animal excrement, and agricultural waste as fuel. Renewable energy is predicted to significantly impact Pakistan's future energy demand (Naqvi et al., 2018).

Because the renewable biomass from woods, woodlots, plantations, and community forests might occasionally be overused when utilized extensively for biofuel. In reality, the overutilization of such woody biomass can result in deforestation and is not always carbon neutral, frequently because of lengthy transportation distances. However, the potential of biomass energy offers long-term solutions for producing electricity, powering many businesses, and delivering energy to residences (Rawat et al., 2024). Widespread deforestation, particularly in Southeast Asia, where natural forests are being cleared to cultivate monoculture crops like sugarcane and oil palms, has been connected to the increasing demand for biomass feedstocks and biofuels. This growth contributes to higher commodity prices, food insecurity, land use disputes, Indigenous communities displacement, and biodiversity loss (Milko, 2025; Global Forest Coalition, 2024). These socioeconomic repercussions emphasize the need to reconsider our dependence on traditional biomass sources and investigate alternative bioresources, such as invasive plant species. Invasive alien plants (IAPs) and other biomass sources are identified as potential feedstocks. Utilizing IAPs for bioenergy has the potential to reduce carbon emissions while simultaneously providing other environmental and socioeconomic benefits (Vera et al., 2022). Their quick growth and high biomass yield make them ideal for bioenergy production, transforming an ecological issue into a possible resource.

Paper mulberry, also known as *Broussonetia papyrifera*, is one example of an invasive species that has spread throughout areas like Islamabad, Pakistan. Initially brought in for urban greening, it has since become the sixth-worst plant invader among the many non-native plant species brought into Pakistan, causing ecological imbalances and health problems because of its allergenic pollen (Qazi et al., 2019).

In light of the increasing ecological burden of invasive species and the pressing need to transition to clean energy, this review aims to explore the dual-use potential of *B. papyrifera* for sustainable bioenergy and fodder uses, as well as to highlight crucial research gaps, policy issues, and its alignment with the United Nations Sustainable Development Goals (SDGs), notably SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 15 (Life on Land).

## Methodology

This study used a narrative review methodology to examine the viability of *Broussonetia papyrifera* (Paper Mulberry) for sustainable bioenergy and fodder uses, especially in the context of invasive species management. Relevant peer-reviewed publications, institutional reports, and international frameworks were examined to combine significant trends, practices, and conclusions. Google Scholar, ScienceDirect, ResearchGate, and institutional databases were used to compile the literature by searching for combinations of keywords like "Paper Mulberry," "*Broussonetia papyrifera*," "bioenergy," "invasive species," "invasive alien plant species," "fodder potential," "biomass conversion," "biomass briquette," and "sustainable development goals. "The search targeted empirical, review-based, and policy-related research from South and East Asia and included literature published in English over the previous 20 years.

The narrative review format provided more freedom to investigate interconnected topics, such as ecological impacts, policy gaps, and socioeconomic opportunities, as opposed to systematic literature reviews (SLR), which adhere to strict inclusion/exclusion standards and quality appraisal checklists. With further assistance from local research that is now under review on the sustainable use of *B. papyrifera* in Pakistan, selected studies were interpreted in light of their relevance to SDGs 7, 13, and 15.

### Invasive Species and Their Global Impact

The definition of invasive species varies between different organizations. According to IUCN, invasive species are organisms humans purposefully or accidentally introduce into new regions, harming native biodiversity, ecosystem services, and economic and social wellbeing (International Union for Conservation of Nature, 2021). The Convention on Biological Diversity (CBD) defines an invasive alien species (IAS) as an alien species threatening biological diversity through its introduction and spread. According to the Food and Agriculture Organization (FAO), an "alien species" and "alien invasive species" refer to species which invade new regions and pose threats to ecosystems and habitats, as well as other species and produce social, economic and environmental damage along with human health risks (Food and Agriculture Organization, 2007). The United States Department of Agriculture (USDA) drive consists of economic and ecological risks, defining them as "invasive species," the Executive Order defines the invasive species as a species that is 1) not native (or alien) to the ecosystem under consideration and 2) whose introduction causes or is likely to cause economic or environmental harm or harm to human health" (National Invasive Species Council, 2001). This shows that although the definitions have slight differences, they all emphasize that these species are not native and have the potential to disrupt ecosystems and/or human activities.

The extensive risks that invasive alien species present worldwide remain unrecognized and undervalued. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) major report reveals that human activities have introduced over 37,000 alien species to global regions and biomes. The conservative estimate shows an unprecedented rate of increase. Over 3,500 harmful invasive alien species exist, posing serious threats to natural ecosystems and human quality of life through their negative impact on nature's essential services. Invasive alien species represent a substantial problem for people everywhere because they are frequently disregarded until too late. The Assessment Report on Invasive Alien Species and their Control, which received approval from IPBES member representatives in Bonn, Germany, shows that invasive alien species caused global biodiversity and ecosystem changes and led to economic costs surpassing $423 billion each year in 2019 while these expenses quadrupled every decade since 1970 (Intergovernmental Platform on Biodiversity and Ecosystem Services, 2023).

The rise in invasion rates is linked to globalization and the growth of international trade. Concerns over invasive species largely stem from their effects at various levels. To begin with, invasive species that become dominant can negatively affect native species far more than dominant native species can, which applies to both land and water ecosystems. Additionally, these impacts can spread to higher trophic levels, resulting in complete changes to communities or even entire ecosystems due to invasions. Furthermore, invasive species can lead to significant economic consequences and pose risks to human health (Thomaz et al., 2015).

Many non-native plant species are introduced into urban environments to create, improve, or restore ecosystem services. However, these species frequently spread beyond their initial locations (Potgieter et al., 2019). They can also create thick monocultures that push out various native plant species, leaving local plants without homes and food. Invasive species can take the place of native plants, disrupt ecological connections and negatively affect the overall functioning and resilience of ecosystems. Moreover, they might change ecosystem processes like nutrient cycling, water availability, and fire patterns. Invasive plants could have different nutrient needs or emit chemicals that alter soil quality and nutrient levels. Native plants often find it hard to thrive in new ecosystems due to challenges in dispersing over long distances, establishing lasting colonies, and adapting to specific climates. Invasive plants with widespread distribution might benefit from climate change because of their ability to adapt and their strategies for gaining new spread methods (Waheed et al., 2024).

The economic burden of IAS is comparable to that of natural catastrophes worldwide. Using the InvaCost 4.1 tool, Turbelin et al. (2023) examined worldwide data from 1980 to 2019. They determined that the economic harm caused by biological invasions was about $1.2 trillion, which is on par with the cost of significant natural catastrophes like storms and earthquakes. It is worth noting that during this time, the expenses associated with biological invasions increased by 702%, surpassing the rate at which damages from natural disasters increased. Henry et al. (2023) evaluated the economic effects of IAS using the InvaCost 4.1 database, which is concentrated on the European Union. Their research revealed that only 259 (~1%) of the 13,331 known invasive species had recorded economic costs, suggesting significant underreporting. They estimated possible damages of $28.0 billion using temporal modelling and macroeconomic scaling to predict that the actual costs might be up to 501% greater than what is currently recorded. Additionally, they predicted that if current trends persist, the cost may reach $148.2 billion by 2040.

The research by Mazza et al. (2014) highlighted the dangers to human health linked to introducing various species, discussing important connections and potential responses. Allergenic plants are among the most frequently researched regarding their influence on human health, mainly focusing on allergenic pollen. Many invasive species are recognized as significant allergens (for instance, *Ambrosia artemisiifolia*). Particular species might lead to contact dermatitis because of chemicals that can trigger skin reactions (such as *Heracleum mantegazzianum* and *Parthenium hysterophorus*) (Lazzaro et al., 2018). Qazi, Iqbal, and Khan (2019) examined the allergy risks associated with pollen from paper mulberry (*Broussonetia papyrifera L.*), an Asian invasive plant that has become widespread in many regions globally. This type of pollen is crucial in causing respiratory allergic conditions, specifically rhinitis and asthma. In Islamabad, a key urban area in Pakistan, the prevalence of allergies linked to *B. papyrifera* pollen is significant.

Because of its enormous diversity of plant and animal life, South Asia is recognized as one of the world's biodiversity hotspots. One of the numerous dangers to South Asian biodiversity is the invasion of plants. Seventy-three invasive foreign plant species representing thirty families and sixty-five genera are documented in the Lesser Himalayas of Pakistan. These species, which have been introduced in various ways, have flourished in various habitats, frequently dominating native plants. South Asia has 392 invasive plant species, with India having the most (145 species), followed by Bhutan (101), Nepal (84), and Pakistan (73). These invasions impact agriculture and livelihoods, change ecosystems, and endanger biodiversity. (Anjum et al., 2022; Bhatta, Shrestha, & Pyšek, 2023; Shabbir, 2021). Some common invasive species across South Asia are listed in Table 1.

**Table 1: Notable, IAPS recorded in Pakistan and other South Asian countries, along with their geographic distribution and key ecological and socioeconomic impacts**

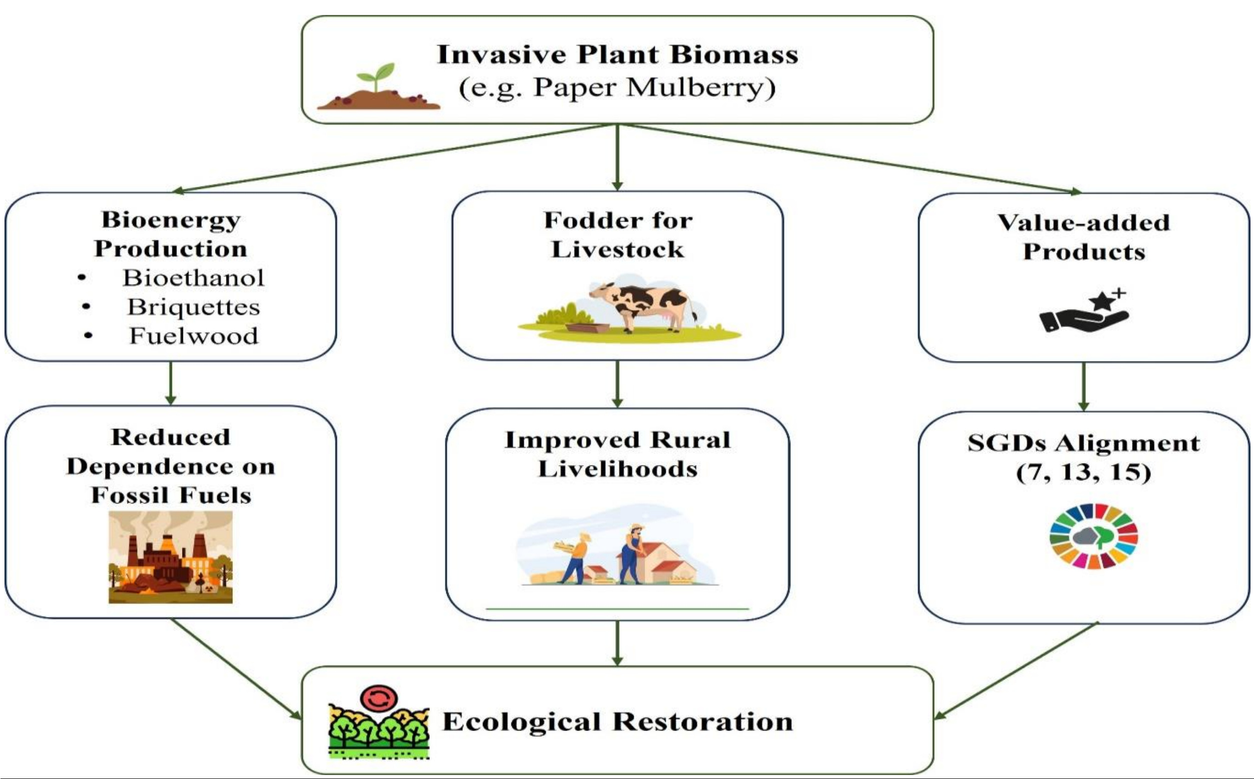
| Species Name | Common Name | Regions (South Asia) | Presence in Pakistan | Key Impacts |
|---|---|---|---|---|
| *Broussonetia papyrifera* | Paper Mulberry | China, Nepal, India, Pakistan | Islamabad, Murree Hills | Respiratory allergies; rule forest edges, displacing natives |
| *Parthenium hysterophorus* | Congress Grass | India, Pakistan, Nepal, Bangladesh, Bhutan | Widespread in Punjab, KPK | Allergic dermatitis diminishes crop yield and pasture productivity |
| *Lantana camara* | Lantana | India, Sri Lanka, Pakistan, Nepal | Himalayan foothills, Margalla Hills | Prevents regeneration of native forests; toxic to livestock |
| *Eichhornia crassipes* | Water Hyacinth | India, Bangladesh, Sri Lanka | Riverine lakes (Sindh, Punjab) | Clogs water bodies, depletes oxygen, and harms fisheries |
| *Prosopis juliflora* | Mesquite | India, Pakistan | Arid zones of Sindh, Balochistan | Invasive in rangelands; alters water availability; unpalatable to livestock. |

Target 15.8 of SDG 15, which aims to protect, restore, and encourage the sustainable use of terrestrial ecosystems, is specifically focused on implementing measures to prevent the introduction and significantly lessen the impact of invasive alien species on land and aquatic ecosystems (Krauss, 2022). Addressing problems like the biodiversity threat and the deterioration of ecosystems brought by IAPS is essential for the conservation and sustainable use of terrestrial ecosystems, which is in line with the goals of SDG 15 (Bhatta et al., 2023).

**Bioenergy Potential of Invasive Species**

IAPs' biomass provides a significant opportunity to utilize it locally (for example, for firewood, furniture, and value-added items) and to scale up the beneficiation by finding a new market (e.g., bioenergy and co-firing biomass pellets). In South Africa, biomass derived from IAPs provides an additional source of feedstock for bioenergy and other allied forest product manufacturing, while also helping to offset investment in invasive alien plants management (e.g., the Working for Water Program of South Africa). Utilization of the rapidly accumulating and copious biomass produced by IAPs, in particular, can help meet the energy demands of the government's larger and more commercially viable initiatives. From a sustainable development perspective, a positive use of biomass from invasive alien plants for bioenergy enables (Figure 1) the capabilities of meeting energy demand from cooking, lighting, space conditioning, transportation, communication, and income generation processes, while also improving human, social, economic, and environmental conditions. If biomass from IAPs clearing projects is used properly and strategically, it will create more jobs, profitable small and medium-sized enterprises (SMEs), and marketable value-added products, in addition to contributing to the reduction in nutrient depletion, fire, and flood risks (Rawat et al., 2024).

**Figure 1: Framework for Sustainable Utilization of Invasive Alien Plant Species**



Several processing steps are required to convert raw biomass into useful energy using the three main process technologies available: bio-chemical, thermo-chemical, and physio-chemical. Biochemical conversion encompasses two primary process options: anaerobic digestion (to biogas) and fermentation (to ethanol). For the thermo-chemical conversion routes, the four main process options presented here are pyrolysis, gasification, combustion, and hydrothermal processing. Physio-chemical conversion consists principally of extraction (with esterification), where oilseeds are crushed to extract oil (Adams et al., 2018; Batista et al., 2023). Biomass can be converted into a whole list of easily combustible and energy-rich products, such as briquettes, pellets, biomass insulated concrete, syngas, or can be directly combusted to generate thermal energy that can be directly used or converted into electricity (Rawat et al., 2024). Briquettes and pellets correspond to the type of solid biomass that is processed by densifying the material, usually discarded or secondary, called waste in industrial and agricultural production processes (Niño et al., 2020). Although biomass can be processed into solid, liquid, and gaseous forms of energy using various approaches (physical, chemical, thermochemical, or biochemical), transforming it into densified fuels such as briquettes and pellets is considered one of the easiest and most promising methods. This is because lignocellulosic biomass is composed of complex molecular structures in the form of lignin, cellulose, hemicellulose, and other extractives, which makes it a bit complex to be chemically, thermochemically, or biochemically transformed into energy. Hence, densifying into briquettes is considered more effective. It is worth noting that adopting briquetting technology has the potential to improve national and domestic income and minimizing household expenditure through the provision of employment opportunities to youths and the elderly who will venture into the production and sale of briquettes (Yunusa et al., 2024). Some examples of IAPs used as bioenergy globally are illustrated in Table 2.

**Table 2: IAPS Utilized for Bioenergy Across the Globe**

| Species Name | Common Name | Region/Example Country | Bioenergy Product | Conversion Method | Reference |
|---|---|---|---|---|---|
| *Broussonetia papyrifera* | Paper Mulberry | China, Pakistan, Thailand | Bioethanol (fruit juice), Briquettes, Fuel wood | Fermentation, Briquetting, Direct combustion | Ajayo et al. (2022); (Bano, Ansari, Umair, under review); Badan, Thepchatri, T., Tanavat, Haruthaithanasan, & Haruthaithanasan, (2020). |
| *Leucena leucocephala* | Ipil Ipil | Sri Lanka | Fuel wood | Fuelwood Value Index | Bandara, Ranasinghe, Perera, Vlosky, & Kizha, (2022). |
| *Parthenium hysterophorus* | Congress Grass | India | Bioethanol | Acid Hydrolysis + Fermentation | Tavva et al. (2016) |
| *Prosopis juliflora* | Mesquite | India, Sri Lanka | Briquettes, Fuel wood | Briquetting, Fuel Value Index | Kumar, & Chandrashekar, (2020); Bandara et al. (2022) |
| *Lantana camara* | Lantana | India | Briquettes | Briquetting | Kumar, & Chandrashekar, (2020). |

Moreover, the use of IAPS in bioenergy contributes to achieving the SDGs, particularly SDG 7 (Affordable and Clean Energy), by increasing access to local renewable biomass sources. SDG 13 (Climate Action), through carbon-neutral fuel production and reduced reliance on fossil fuels. SDG 15 (Life on Land), by encouraging sustainable management of invasive species and restoration of affected ecosystems.

**Paper Mulberry as a Bioenergy Source**

*Broussonetia papyrifera* (L.) L'Hér. ex-Vent. (Moraceae), commonly known as the Paper Mulberry, is a medium to large deciduous tree indigenous to East Asia, especially Japan and China. It is also present throughout the world in tropical and subtropical areas. It is ranked among the top six invasive species in Pakistan and is regarded as one of the most troublesome plant invaders (Waheed et al., 2024; Qureshi et al., 2014). In an attempt to enhance landscape quality, a plan known as the Greenway concept began in the 1960s in Islamabad, the federal capital of Pakistan, to renovate the streets with plantations. However, this initiative ultimately harmed native plant diversity (Qureshi et al., 2014; Qazi et al., 2019). Paper mulberry trees are the main cause of pollen allergies in Islamabad. Paper mulberry trees make up an estimated 60 to 70 percent of Islamabad's foliage. The majority of those who experience extreme allergic reactions, such as asthma attacks, are allergic to the pollen of paper mulberry trees. Ever since pollen allergy was identified as a danger to human health in Islamabad, the paper mulberry tree has been the center of attention (Hussain & Shah, 2020; Qureshi et al., 2020). Other appealing characteristics of this tree are its robust germination capacity, fast growth rate (1 m in height and 1–2 cm in diameter each year), high biomass output, abundant regeneration potential, excellent tolerance to stressful environments, and little maintenance needs. Paper mulberry (PM) trees are cultivated in both monoculture and agroforestry settings, where they serve a variety of purposes, including as soil enhancers or fallow crops, intercropping species, afforestation trees, urban or avenue plantations, and as exceptional raw materials for creating high-quality paper, textiles, medicines, and modern biomaterials. The fruits of the PM tree, which are rich in soluble sugars, are not as thoroughly studied as other parts of the tree, such as the stem, stem bark, and roots (Ajayo et al., 2022).

The paper mulberry's wood has good fueling characteristics. Badan et al. (2020) conducted a Thailand-based study that found the species to have a high heating value (4,585 Cal/g), moderate density (0.32 g/cm$^3$), low ash content (1.72%), and high volatile matter (81.37%). These are all crucial characteristics of bioenergy species. Its high lignocellulosic content, which is mostly made up of cellulose, hemicellulose, and lignin, makes it ideal for pellet and briquette densification.

In a related important Chinese study, Ajayo et al. (2022) investigated the fermentation-based biochemical conversion of paper mulberry fruit juice (PMFJ) for bioethanol production. The findings indicated that this nutrient- and sugar-rich PMFJ has excellent potential as a viable feedstock for bioconversion to ethanol, as it produced competitive ethanol yields with a productivity of 4.7 g/L/hr and compared well with the juices of conventional sugar energy crops. As a vital native tree in China, its non-food fruit juice can be effectively utilized in the field of 1G ethanol production, which will increase feedstock variety and may hence help fulfill the demand for cleaner, more affordable, and sustainable energy.

In addition, the bioenergy potential of paper mulberry biomass and its value-added products in Pakistan has been the subject of recent field research, which is currently being reviewed. This research evaluates the physical and combustion-related characteristics of the biomass under different binder types, solid-to-binder ratios, and biomass ratios (Bano et al., under review). While full results are pending, initial findings reinforce PM's potential as a densification able biomass for sustainable biofuel applications.

**Nutritional Potential of Paper Mulberry as Fodder**

*Broussonetia papyrifera* has useful possibilities as a forage plant for animals in addition to its function as a biofuel source.

Paper mulberry is highly adaptable to a range of environments. The biomass yield of paper mulberry can vary from 45 to 120 tons per hectare. Most crucially, paper mulberry is highly nutritious. Based on dry matter (DM), paper mulberry can contain 18–24% crude protein (CP), which is similar to alfalfa. Additionally, it contains 44.71% neutral detergent fiber, 23.9% acid detergent fiber, 2.92% ether extract, and 11.67% ash. In addition, it is high in vitamins, amino acids, antioxidants, antibacterial agents, and digestible fiber. As a result, paper mulberry could be a viable option for a protein feed resource to help alleviate the forage shortage. Nevertheless, due to its high moisture and protein content, paper mulberry is prone to spoiling, highlighting the need to find an efficient way to preserve it (Guo et al., 2021; Osman et al., 2022).

In recent years, several studies have shown that paper mulberry-based diets can improve feed utilization and livestock productivity (Guo et al., 2021).

According to a study on grass carp (*Ctenopharyngodon idella*), the functional possibility of paper mulberry in aquafeed compositions is supported by its dietary addition, which notably improved muscle quality and growth performance (Tang et al., 2021). In a similar vein, in rabbit production systems, the partial substitution of alfalfa with PM leaf meal enhanced meat quality and digestion in young rabbits, without negative impacts on feed intake or weight increase (Wu et al., 2019). The favorable nutritional profile of PM supports these results. According to another study, higher levels of paper mulberry leaf meal in rabbit diets enhanced nutrient digestibility and carcass traits, indicating that it can be a good forage replacement that does not reduce productivity (Osman et al., 2022). It also has a strong capacity for germination, a rapid growth rate, a high biomass yield, a lot of regeneration potential, great tolerance for challenging conditions, and very low maintenance requirements (Ajayo et al., 2022).

Preliminary research from Pakistan, which is currently being reviewed, has also examined the nutritional profile of paper mulberry leaves, producing results that are comparable to those of East Asian studies (Bano et al., under review). According to the research, using PM in this manner would help address the problem of controlling invasive species while also furthering broader goals like environmental conservation, energy diversity, and food security.

However, although the short-term outcomes are encouraging, more study is required to evaluate the long-term effects of PM-based diets on animal health, reproductive performance, and possible anti-nutritional factors in different species.

## Socioeconomic and Policy Perspectives

**Socioeconomic Opportunities and Challenges**

Using invasive plant biomass like *Broussonetia papyrifera* creates opportunities for rural livelihood development, particularly in communities that rely on traditional biomass. Employment chances for women and youth can be generated through livestock fodder processing centers, small-scale biorefineries, or decentralized briquetting units, which also help tackle rural unemployment and advance gender-inclusive green economies (Rawat et al., 2024).

Biomass management initiatives such as Working for Water and rural energy cooperatives in nations like India and South Africa have demonstrated that biomass valorization from invasive species can enhance energy access, lower indoor air pollution, and increase household income (Vera et al., 2022; Kumar & Chandrashekar, 2020). Nonetheless, awareness, infrastructure, and market connectivity issues continue to hinder implementation in nations like Pakistan.

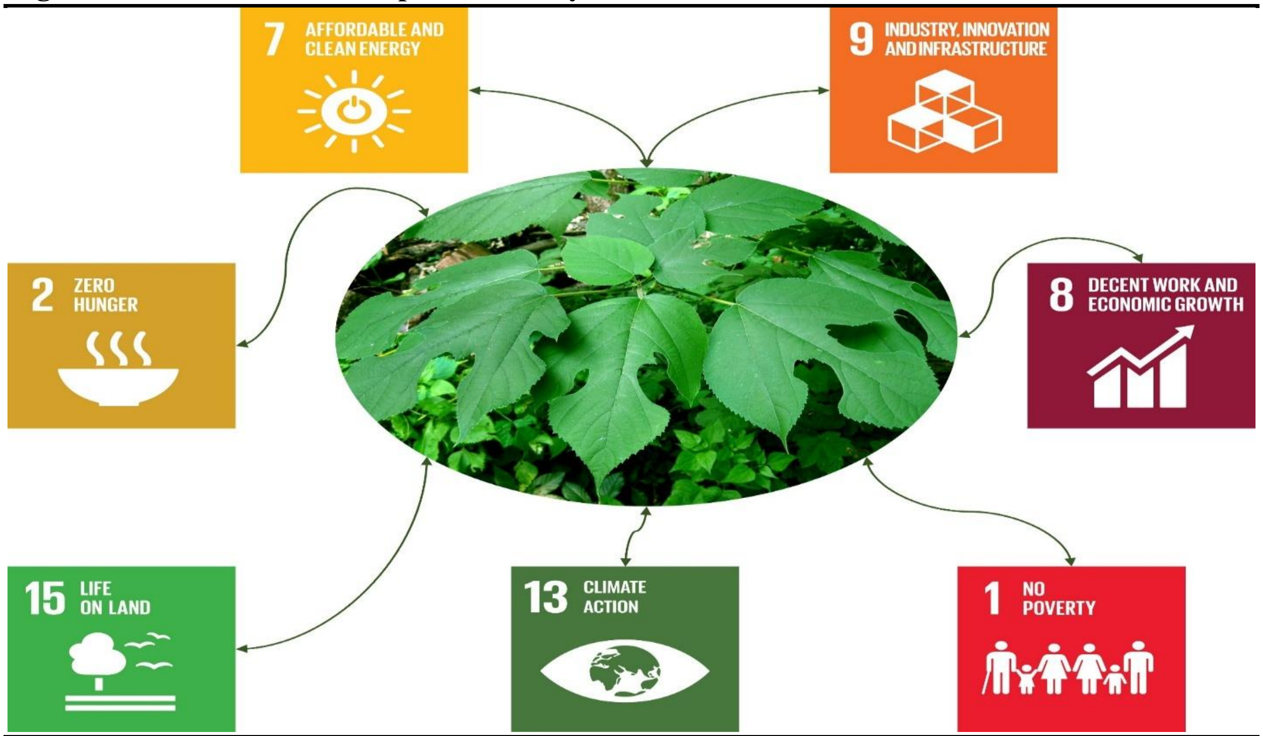
**Sustainability and SDG Integration**

As previously stated, the valorization of IAPs is in line with several specific SDGs (

Figure ***2***):

i. SDG 7 (Affordable and Clean Energy) by facilitating renewable energy access through biomass
ii. SDG 13 (Climate Action) by decreasing deforestation pressure and adopting carbon-neutral fuel substitutes.
iii. SDG 15 (Life on Land) by restoring native biodiversity and managing invasive species (Bhatta et al., 2023).

**Figure 2: Contribution of Paper Mulberry Utilization to the UN SDGs**




Additionally, establishing circular systems that utilize invasive biomass locally improves ecosystem-based adaptation methods to climate change and decreases reliance on fossil fuels (He et al., 2022; Latterini et al., 2022).

**Policy Recommendations**

Numerous recommended policy-level actions are aimed at the responsible and ethical use of IAPs:

1. *Recognition of Invasive Biomass as a Renewable Resource:* National policies governing forestry, agriculture, and energy should treat invasive biomass as a legitimate feedstock for energy and animal food.

2. *Promoting Small-Scale Innovation:* The IAP-affected areas should receive subsidies for microfinance and the distribution of technology (e.g., mobile briquetting units and fodder processors).
3. *Cross-Sectoral Collaboration:* Merging the energy, agriculture, forestry, and livestock sectors to develop multipurpose management strategies.
4. *Ecological Safeguards:* Verify that biomass removal does not further deteriorate ecosystems or impede natural regeneration.

**Future Directions and Research Gaps**

There are still many research gaps, aside from growing interest:

1. The long-term ecological consequences of large-scale biomass extraction from invaded areas are still under-researched.
2. Lifecycle assessments (less) cannot quantify the net carbon, water, and energy footprints of invasive biomass conversion systems.
3. There is still a knowledge gap regarding the feed safety of PM-based feed, particularly about various livestock species and climatic areas.
4. More locally contextualized techno-economic analyses are required to assess the viability of biomass-based rural businesses in South Asia.
5. Few policy implementation studies address practical obstacles in invasive biomass markets, and these are essential for expansion.

Ongoing research, such as a recent study on the briquette and fodder potential of *B. papyrifera* in Pakistan, helps address these gaps and emphasizes the need for region-specific information to guide future recommendations (Bano et al., under review).

## Discussion

This review highlights the undiscovered yet valuable role of IAPS, such as *Broussonetia papyrifera*, in promoting sustainable development strategies, particularly in the Global South. Due to its positive physicochemical and combustion characteristics, existing studies have demonstrated its high bioenergy potential (Adams et al., 2018; Badan et al., 2020), and fruit juice-based fermentation produces promising bioethanol yields (Ajayo et al., 2022). Several animals feeding trials, including those involving rabbits and grass carp, have also demonstrated the species' nutritional profile, indicating that it may be a viable alternative fodder option (Wu et al., 2019; Tang et al., 2021; Osman et al., 2022). Despite the encouraging results, the widespread usage of IAPS continues to be hampered by considerable obstacles. These include restricted public understanding, fragmented policy strategies, ecological uncertainties surrounding long-term biomass removal, and the absence of lifecycle and techno-economic evaluations specific to local circumstances (Kumar & Chandrashekar, 2020; Vera et al., 2022). Furthermore, the dual role of IAPS as both ecological threats and potential resources creates a policy conundrum in which utilization must be balanced with biodiversity protection and restoration initiatives (Bhatta et al., 2023; Krauss, 2022).

Going forward, interdisciplinary approaches that combine forestry, energy, agriculture, and environmental governance are vital. Integrating community-level initiatives, such as sustainable harvesting and small-scale bioenergy entrepreneurship, with top-down policy support might transform IAPS from unmanaged burdens into managed ones. These circular resources contribute significantly to SDG targets 7, 13, and 15.

## Conclusion

The widespread invasion of plants like *Broussonetia papyrifera* poses significant ecological and economic issues, but it also offers understudied prospects for sustainable use. This review emphasizes the dual-use potential of Paper mulberry as a nontraditional feed source and a bioenergy resource. Particularly in resource-poor areas like South Asia, its rapid growth, high biomass production, and nutrient-dense composition allow it to provide alternatives for livestock feed and clean energy solutions.

The valorisation of paper mulberry is consistent with several SDGs, particularly SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 15 (Life on Land). However, increasing such use requires multisectoral cooperation, focused studies on feed safety and environmental effects, and the development of supportive regulations that view invasive biomass as a valuable resource rather than waste.

Although preliminary studies and worldwide case studies point to a substantial contribution of paper mulberry to ecological restoration and rural development, the safe and sustainable implementation of paper mulberry still depends on long-term data, evaluations of economic viability, and analyses of life cycles. With careful planning and investment, invasive species like *Broussonetia papyrifera* can be converted from a danger to an asset for sustainable development.

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