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Review

Optimizing the Benefits of Invasive Alien Plants Biomass in South Africa

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Abstract: The current political situation in South Africa is seeking opportunities to promote sustainable development and use of renewable resources for energy, poverty alleviation, economic development, and environmental protection (e.g., mitigation of greenhouse gas emissions). The present study is based on a critical literature review and synthesis of policy advice in South Africa. The study comprehensively examined the knowledge base and gathered relevant empirical findings and perspectives so as to identify the gaps, trends, and patterns in the optimal management and utilization of invasive alien plants (IAPs) biomass, thereby supporting evidence-based practice. Additionally, the literature review was supported by the first-hand experience of invasive alien plants management and its biomass utilization. This research proposes long-term options for optimizing the costs and benefits of invasive alien plants biomass and meeting rising energy demand. Biomass from the country's approximately 300 "Working for Water (WfW) Projects" might be used for bioenergy, firewood, charcoal, and other value-added forest products, both for internal and international use. The extraction and use of biomass from invasive alien plants for green energy and other valuable products would aid in the elimination of hazardous invasive species and reduce the amount of fuel in the fields, as well as fire and flood threats. Biomass from invasive alien plants clearings can be distributed to rural regions and informal settlements as a supply of firewood with the aim of reducing reliance on nearby forests, conserving the environment and biodiversity, minimizing forest degradation, supporting climate change, and enhancing energy efficiency and wood waste management (e.g., recycling and prevention) for green economic development and industrial transformation. The findings of this study imply that for competitive biomass-to-energy conversion and bio-economic applications for the use of invasive alien plant biomass, cost management, particularly for transportation, and significant regulatory incentives are essential. In addition, effective policy instruments that aid in the promotion of innovative systems and knowledge generation are required so that biomass can be optimally used for bioenergy and other competitive bio-economic applications.

Keywords: bioenergy; bio-economy; value-added products; value chains; forest products; Working for Water programme; sustainable development

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1. Introduction

Energy consumption is a basic human necessity that is directly linked to quality of life [1–3]. To date, there is still a high reliance on unsustainable fossil fuels, which are non-renewable and environmentally unfriendly, e.g., by exacerbating greenhouse gas emissions and climate change [2,4–6], and which are also concentrated in politically volatile regions [7,8]. As a result, currently there is a global effort to promote and use renewable energy sources [3,9–11]. Biomass is a renewable source of energy, and is being increasingly utilized to meet society's and industry's growing energy demands [4–6,12–15]. Some countries have already made significant progress in this regard (the United Kingdom, the United States, and Germany) [8,13], and many more are on pace to do so. Furthermore, if dealt with in the context of the food, water, and energy nexus, this method of using biomass for bioenergy is helpful for Earth stewardship by avoiding land-use changes and food security challenges [2]. In South Africa, biomass derived from invasive alien plants (IAPs) could provide an additional source of feedstock for bioenergy and other allied forest product manufacturing [6,16–19], while also helping to offset investment in invasive alien plants management (e.g., the Working for Water Programme of South Africa), since the renewable biomass from woodlands, woodlots, plantations, and community forest can sometimes be overexploited during its large-scale use for biofuel. Overexploitation of such woody biomass can, indeed, lead to deforestation and is not entirely carbon neutral, often due to long transport distances [6,20]. Nonetheless, biomass energy potential provides long-term options for generating electricity, powering several industries and supplying energy to homes [6,14,19,21]. Furthermore, the South African government intends to offer energy to each household, whether they are located on the outskirts of rural areas or in urban informal settlements, in line with the UN's "Sustainable Energy for All" Initiative [2,4–6,14,22,23]. Energy demand has been rising in recent years as a result of rural–urban migration and community modernization, and this trend will continue to persist into the future. Furthermore, a huge number of rural houses are still off the grid. As a result, the country needs action in researching, piloting, and putting into the use of new and sustainable energy resources so as to meet the country's growing energy demands [4–6,14].

Invasive alien plants have been gaining dominance in the natural and managed ecosystems worldwide as shown in the Millennium Ecosystem Assessment [6,24–26]. Several ecosystems in South Africa have been disturbed to varying extents, inclusive of the impact of invasive alien plants [27–31]. Invasive alien plants are now a global issue and have the potential to alter ecosystems and inflict loss of biodiversity [24,25,32–34]. They are now dominating many ecosystems (both terrestrial and aquatic) in South Africa, effecting reduced water flow in rivers where they are common, and have been recognized as a national problem [6,30,31]. The "Working for Water Programme (WfW)", a systematic control and management program of invasive alien plants in South Africa, was conceived in 1995, shortly after South Africa gained democracy, with the goal of conserving ecosystem services (e.g., water) and biodiversity, and addressing the country's socio-economic concerns [6,30]. In a broader sense, this program is aligned with the inclusive development paradigm [35] and is recognized globally [30,36] for achieving socio-political goals (e.g., green jobs, skills development, health and safety, and rural well-being development), as well as ecosystem services (e.g., water, biomass, and biodiversity management) [6,30,34,37]. The WfW Programme has created about 250,000 direct jobs, primarily seasonal, and treated about >25,000 km^2 of land area [38]. Additionally, the harvesting of invasive alien plant biomass, transportation, processing, and use will create more jobs in the future.

The current biomass management strategy, which is focused mainly on on-site burning of the biomass of invasive alien plants, is insufficient to deal with the increasing extent of the fuel load. On-site biomass bucking, chipping, and stalking have been typically practiced to minimize fuel loads and eliminate fire and flood concerns [34,35]. The cost of not removing biomass from places of accumulation has created a hazard from fire and flooding risks. Intensive forest fires have reduced vegetation growth, harmed soil structures and nutrients, and exacerbated soil erosion and land degradation [21]. However, there is a significant opportunity to utilize invasive alien plants' biomass 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) [4,5,14]. As a result, this study investigates, for the first time, potential niche markets and optimization of multidimensional uses and benefits of biomass derived from invasive alien plants in South Africa, in addition to constraints associated with the use of biomass.

2. Methodology

This study is mainly based on a critical literature review and synthesis of policy advice. Therefore, the first step was delimitation of the thematic focuses of the study that resulted in the following themes: sources of biomass, distribution, and abundance; major invasive species and avenues of the utilization of invasive alien plants; biomass for energy (theory and applications), including trends; existing and emerging challenges, techno-economic insights, and the policy response; and synthesis of evidence-based advice (to identify potential knowledge gaps) for the framework of invasive alien plants biomass utilization.

Identification of keywords was the next step, in which the following were obtained: invasive alien plants, biomass, bioenergy, firewood, charcoal, biochar, gasification, cogeneration, electric generation, bio-economy, private land owners, legislation, Act, Working for Water Programme, value-added products, value chains (VCs), biomass utilization, poverty reduction, sustainable development, eco-industry hubs, and South Africa (SA).

The literature review was conducted using combinations of two or more of the keywords by comprehensively searching throughout the following databases: grey literature (archived from government and private office repositories) and publication databases; Google Scholar; ResearchGate; Web of Science; PubMed; ScienceDirect; Scopus; SpringerLink, Elsevier; book chapters; and proceedings.

In the review process, the knowledge base was examined, gaps, trends, and patterns in the subject were noted, empirical data and viewpoints were gathered to support evidence-based practice, and topics needing further investigation were identified. Keywords and abstracts from the databases' literature were matched during the literature review process. A total of 217 full-text publications were downloaded and visually scanned; the relevant research papers and reports were screened and kept for the analysis and evidence-based synthesis. Out of 217 articles, 128 met the purpose of this research, and their contents were duly read and important information (i.e., qualitative and quantitative data) about optimizing the benefits, existing and emerging challenges, and multiple uses of invasive alien plants' biomass was extracted. Mixed data analysis methods (i.e., qualitative and quantitative) were used. Meta-analysis and qualitative analysis (e.g., grounded theory, narrative analysis, and meta-ethnography) were applied to obtain qualitative and quantitative data for the sake of pattern and trend extraction, as well as for qualitative forecasting and synthesis of policy advice. The variables of biomass products (such as green energy, charcoal, biochar, firewood, furniture, and wood pellets), eco-industry hub, building materials, biomass market, industrial inputs for further process, and chemical and agriculture inputs were evaluated qualitatively. The pertinent information was, thereafter, systemized in order to advance the knowledge and facilitate the theory and discussion developed for the present study. The information used was connected to the objectives of the study, methods, and the qualitative and quantitative results. All the species mentioned in the study are invasive in nature and categorized based on their severity and the activities [16,17,34,35]. The literature review was coupled with and supported by first-hand experience of invasive alien plants management, invasive alien plants biomass use, and optimizing the benefits of practices gained from personal observations, stakeholder engagement, and consultations. The extracted valid contents were collated, organized, analyzed, and synthesized. The variables and information obtained are presented systematically and narrated in this review paper.

3. Results and Discussion

3.1. Significance of Utilizing Biomass from Invasive Alien Plants

South Africa is situated in a semi-arid region of the world, where water is meagre, weather patterns are shifting (e.g., droughts) as a result of climate change impacts, and coal-fired energy systems provide 85% of the country's electricity [21,39]. Extreme weather events (e.g., droughts and climate change) have altered rainfall patterns and impacted the energy supply, as well as the economy and people's livelihoods [34,35]. As a result, the country is facing challenges in meeting international obligations (for example, climate change mitigation and adaptation measures, biodiversity conservation targets, and global development goals), as well as being vulnerable to fluctuations in the prices of oil and gas [4,5,21]. Historically, the South African economy has been heavily reliant on mining, which has consumed a significant quantity of energy derived from unsustainable coal, in addition to everything else [5,6,40]. The rising demand for energy, along with the usage of unsustainable fossil fuels to meet that demand, necessitates the search for alternate and sustainable energy sources, one of which is abundantly available biomass [4,5,14]. Biomass appears to have the potential to be a future source of sustainable green energy [6,12,13,15]. However, there are just a few scholars and organizations that have studied the multidimensional viability of biomass for energy [6,14,15,21]. In comparison to other renewable energy sources (e.g., hydropower, wind, geo-thermal, and solar), biomass now provides the highest amount of energy on a global scale [11,22,41]. The contribution of biomass is even much higher (about 30%) in tropical Africa [41].

South African energy and electric power systems have three major problems: (i) under supply of electricity, (ii) pressure to increase electricity supply, and (iii) increasing demand from the energy intensive economy of South Africa, which is being met mostly through the use of coal at the expense of environmental harm [5,14,21,42]. Competitive replacement of unsustainable coal with sustainable sources such as biomass is needed to address the dire energy situation in the country [6]. Utilization of the rapidly accumulating and copious biomass produced by invading invasive alien plants, in particular, can help meet the energy demands of the government's larger and more commercially viable initiatives [21,35,42]. From a sustainable development perspective, a positive use of biomass from invasive alien plants for bioenergy enables capabilities of meeting energy demand from cooking, lighting, space conditioning, transportation, communication, and income generation processes [3,14,22], while also improving human, social, economic, and environmental conditions [43]. The disadvantage is that, if not utilized properly, it can burden the environment, being a source of eco-toxins and greenhouse gas emissions, and disturb equilibria in ecosystems [20]. Furthermore, technological advancements favor a sustainable transition from a fossil fuel-based economy to a more bio-based green economy [4,6,14,22].

Utilizing plentiful, cheaper, and more environmentally friendly energy sources makes it simple to adopt and employ energy-efficient and cost-effective technologies, which are essential for achieving both energy security and environmental sustainability [3,14,43]. Indeed, to improve the human, economic, social, and environmental conditions of the people, a greater level of provisions of sustainable energy services is indispensable in the bio-economy [4,5,15].

3.2. The Sources of Biomass in South Africa

Commercially, South Africa has been using biomass residues such as bagasse for electricity generation in the sugar industry [14]. In the plantation-based pulp and paper business, residues from biomass processing, such as scrap wood and sawdust, are also being used [4,5]. Similarly, the biomass generated and significantly amassed from the removal of invasive alien plants can be used to generate bioenergy and other value-added goods for local and international markets [6,19]. If biomass from invasive alien plants 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 [6,19,30,34]. These schemes are particularly politically appealing and smart but they can only be implemented if they are adequately funded, subsidized, and paid constant attention [16]. It is expected that biomass energy has promise in enabling South Africa to improve the sustainability goals, efficiency, and health of its energy systems in the future [4,5,14]. Currently, residues from small-scale and large-scale sawmills are the main source of feedstock for biomass energy plants [41]. Specifically, the biomass from invasive alien plant clearings could supplement the feedstock for bioenergy, along with agriculture and forestry biomass in South Africa [4,5,44].

Existing and new, similar energy plants can take advantage of abundant and widely distributed biomass accumulation in various clearing sites to meet energy demand in a sustainable manner and to reduce the transportation costs, thereby reducing greenhouse gas (GHG) emissions [4–6,14,30]. In addition, if a scarcity of biomass arose in the near future, as invasive alien plants are considered to be non-renewable and destined to be eradicated in South Africa, then a large quantity of industrial wood waste, along with agriculture and forestry biomass, could be continually used to sustain the bioenergy feedstock [44]. Invasive alien plants' coverage and density, on the other hand, have been rising in various sections of the country [34]. Even places designated for conservation have been invaded, and areas that have not yet been affected may soon be invaded shortly owing to global environmental change [45]. In South Africa, 80 percent of land is privately owned, the majority of which is affected by invasive alien plants [34,35]. The biomass from these plants can be used as feedstock for the production of electricity and other products. Other sources of bioenergy feedstock in South Africa are agriculture and forestry, which are widely developed and produce a large amount of biomass [4,5,44]. In a nutshell, the sustainable use of biomass from all sources can support efforts of climate change mitigation, biodiversity conservation, enhancement of energy efficiency, and wood waste management for green economic growth and environmental sustainability of the country [46]. Conversely, considering the economic and promising market and energy value of invasive alien plants, such high-potential species might be cultivated under controlled conditions in the face of an attractive market while duly obeying the laws. Alternatively, invasive alien plants are short rotation crops and accumulate a higher amount of biomass in a short period of time; thus, invasive alien plants are considered a significant source of carbon. Therefore, the eradication of invasive alien plants will result in a net loss of carbon and a trade-off between GHG emissions, conservation of ecosystem services (i.e., water), and socio-economic development [6].

3.3. The Distribution, Abundance and Major Invasive Species

Invasive alien plants' distribution, abundance, and habitats in South Africa are depicted in Figure 1. The eradication of invasive alien plants is compulsory in South Africa by law, which clearly illustrates that the large supply of biomass from invasive alien plants is directly linked to the heavy invasion areas, species, and their abundance in the country. Figure 1 is further helpful in understanding the application, scope, and scaling up of biomass benefits and applications. The area where invasive alien plants are densely distributed can be used for bioenergy purposes and other allied products [4,5,19]. Figure 1 shows that invasive alien plants have heavily invaded the Western Cape, followed by KwaZulu-Natal and the Eastern Cape. The availability of biomass was projected to be highest for *Eucalyptus* spp. at the national and species level, followed by *Acacia* spp., *Pinus* spp., *Poplus* spp., *Salix* spp., and *Prosopis* spp. The Eastern Cape has the most *Acacia* spp. biomass, followed by KwaZulu-Natal, the Western Cape, and Mpumalanga. The biomass of this species has been found to be lower in other provinces. Furthermore, the biomass supply for indigenous bush invasion is estimated to be around 169 Tg (The Council for Scientific and Industrial Research; www.csir.co.za; accessed on 15 July 2021).

Eucalyptus spp., *Acacia melanoxylon* R. Br., and *Pinus* spp. are among the invasive alien plant species in South Africa that have market values in terms of use for furniture, planks, and garden material, whilst *Acacia mearnsii* De Wild and other *Acacia* spp. have firewood values. As a result, scraps from *Eucalyptus* spp., *Acacia melanoxylon*, and *Pinus* spp., as well as biomass from other *Acacia* spp., might be used directly to generate bioenergy, charcoal, biomass pellets, and other associated products (e.g., biomass insulated concrete) [4,5,19]. *Acacia longifolia* (Adrews) Wild. (58.48 t ha^{-1}) had the largest rate of biomass production, followed by *Acacia mearnsii* (31.73 t ha^{-1}) and *Acacia saligna* (Labill.) H.L. Wendl (23.20 t ha^{-1}) [16,17]. The maximum rate of biomass production was calculated for *Eucalyptus* spp.-*Acacia* spp.–*Pinus* spp. associations (86.51 t ha^{-1}), followed by *Eucalyptus* spp.–*Acacia* spp. (84.94 t ha^{-1}) and *Acacia* spp.–*Pinus* spp. (71.97 t ha^{-1}) in combinations where plant species were grown in association. Species and their plant associates are also important in the production of biomass that can support bioenergy and the bio-economy [16,17] in the provision of sustainable forestry and the protection of valuable forest resources and biodiversity in the country [46].

3.4. Optimizing Benefits as Biomass Applications and a Niche Market

Biomass can be converted into a whole list of easily combustible and energy-rich products such as briquettes, pellets, charcoal, biomass insulated concrete, syngas, and bioethanol, or can be directly combusted to generate thermal energy that can directly be used or converted into electricity [5,6,14,15,19]. Figure 2 illustrates a framework for invasive alien plant biomass applications. It comprises the biomass resources, harvesting, value-added forest products, processing of the biomass, final products, and biomass market.

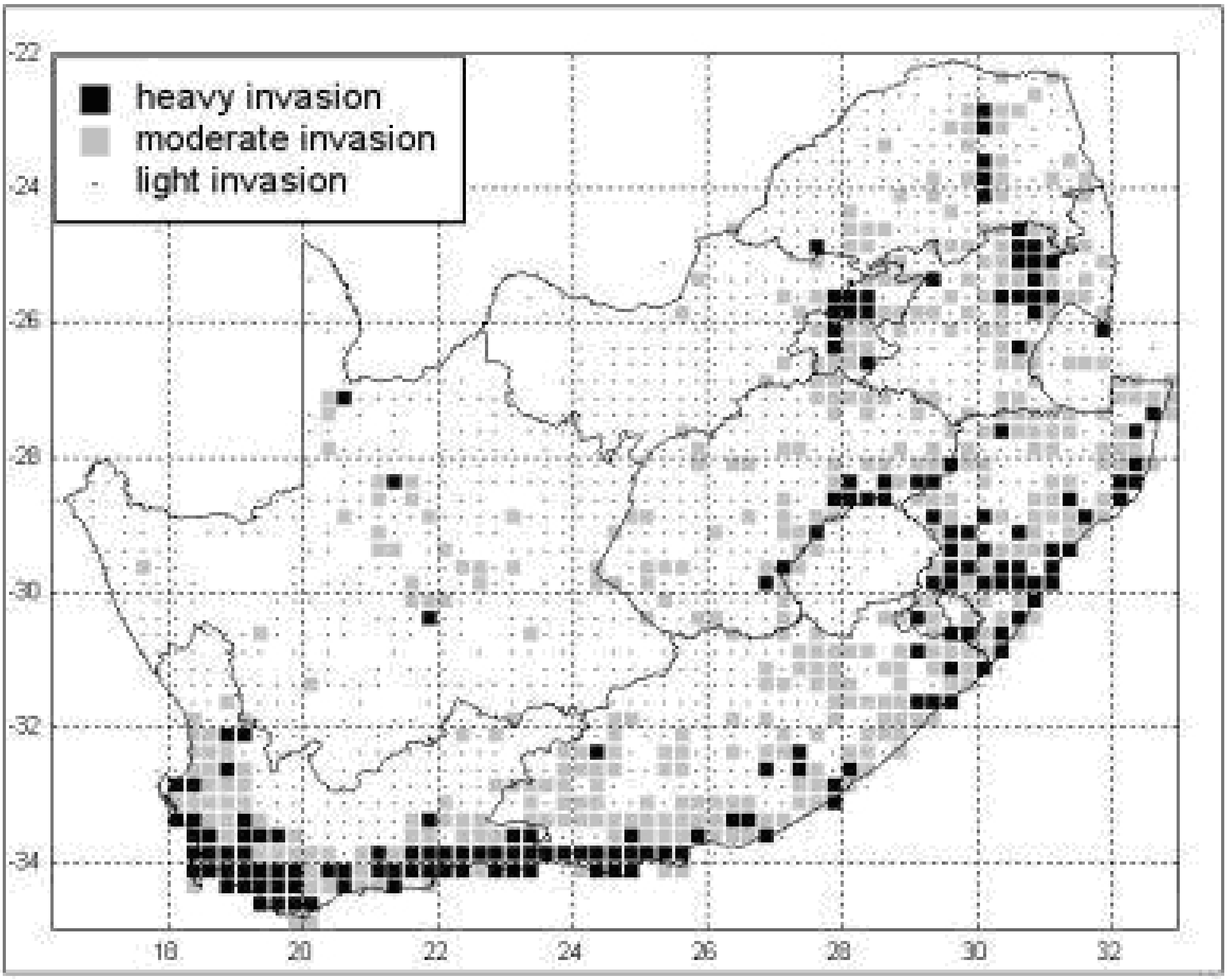

Figure 1. The distribution and abundance of invasive alien plants in South Africa. Source: Southern African Plant Invaders Atlas; http://www.arc.agric.za; accessed on 17 July 2021.

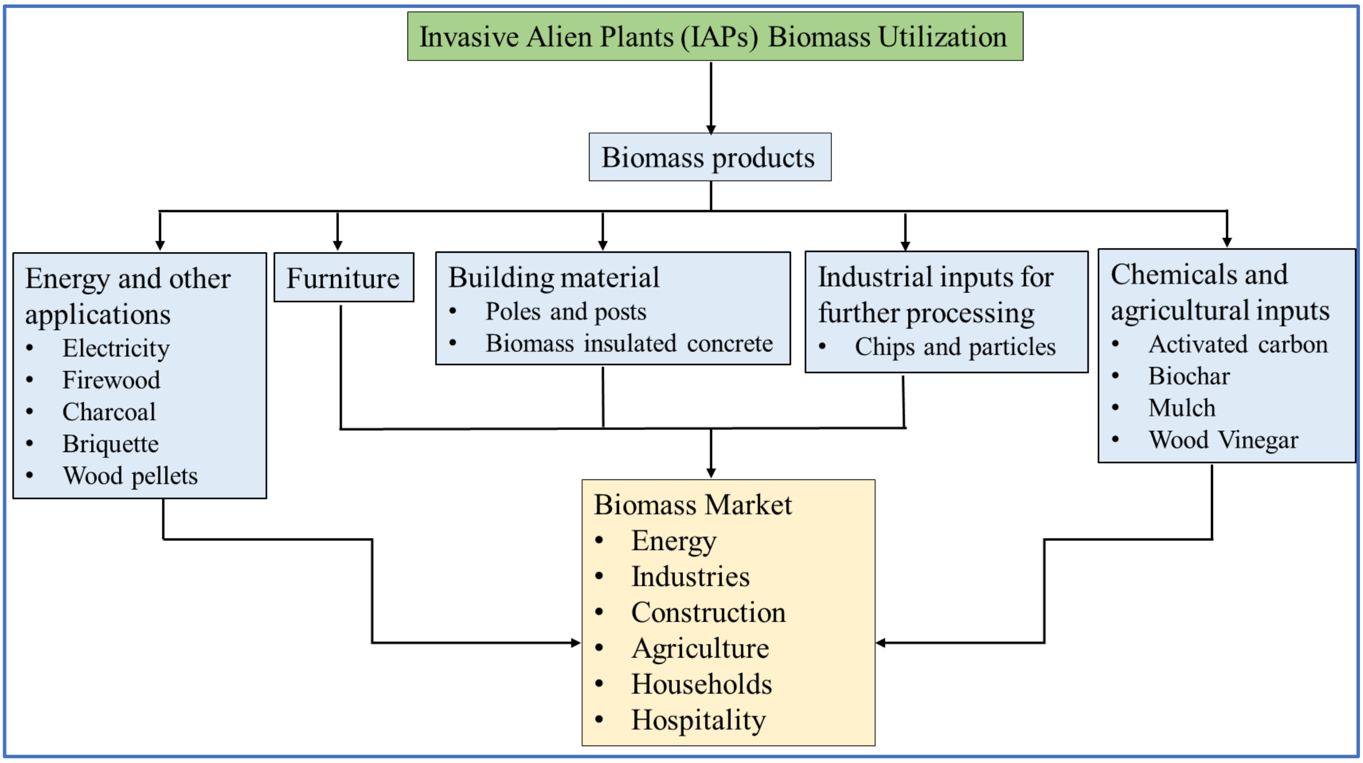

Figure 2. A framework for the use of invasive alien plant biomass for energy and forest product development by adopting advanced technologies (e.g., gasification or pyrolysis), thereby contributing to the green economy, green energy, environmental sustainability, and reduction in flood and fire risks.

3.4.1. Energy (Power Generation, Heat and Steam, Boilers, and Drying)

Gasification has been found as one of the successful mechanisms for biomass-to-energy conversion. The most technically and economically convincing energy option for a carbon-neutral economy is biomass gasification and final conversion to electricity [6,14]. For example, by 2013, renewable energy generation, which included biofuels, accounted for 4% of total power generation; but by 2020, that figure was expected to have risen to 13% [21]. This is an easily achievable target when the abundant biomass feedstock is considered, which is a key enabler for bioenergy [6,15]. The government seeks to greatly improve everyone's access to energy in order to alleviate poverty [47]. The government of South Africa's "biomass to bioenergy" effort is depicted in Table 1, which highlights the goals, applications, and sources of biomass as a feedstock that could help to enhance energy, the bio-economy, rural development, and long-term livelihoods [4,5]. In addition to the vast quantity of potential biomass feedstock that is being amassed by invasive alien plants, a significant quantity of biomass leftovers is also available in more than 200 sawmills located across the country. However, the inaccessibility of the biomass is a major constraint and the use of biomass is expensive due to the high logistic cost for a country like South Africa [6]. Thus, biomass-derived products need to be incentivized in South Africa [8,48].

To date, biomass-to-energy generation in South Africa is still on a trial basis, and these trials demonstrate a promising potential. Despite severe sustainable energy shortages in South Africa, biomass energy has not been fully harnessed due to a number of hurdles [4,5,14,40]. Nonetheless, the power generated by invasive alien plant biomass could meet some of the country's bioenergy needs and help support the reduction in fire and flood risks, ensure sustainable forestry, and safeguard the biodiversity for green economic development and industrial transformation [6,34,46]. The use of biomass for bioenergy needs greater dedication, better incentives, and a market, particularly in the local area, along with enhanced promotion of available technologies [15]. Furthermore, to discuss and overcome the obstacles and see better perspectives, a synergy between multiple actors and players, including technology suppliers and research institutes, is essential [48]. Invasive alien plant biomass as an industrial feedstock might be converted into adequate and clean energy, as well as being used for the creation of additional value-added forest products, employing appropriate energy-efficient technology for green economic development and industrial transformation [4,5,14,19,46].

Table 1. Biomass-to-bioenergy initiative by the government in South Africa.

Name of the Organizations	Objectives	Applications	Biomass Sources Focuses on	Sources
Department of Environmental Affairs	To produce various forms of bioenergy sustainably (e.g., biogas, woodgas (gasification), pellets, charcoal and firewood, employment, and skills development	Cooking, water heating, space heating, industrial heating for processing, electricity generation, transportation fuel, chemical industries, fertilizers	Waste water treatment plants, landfill sites, pulp and paper industries, wood mills and furniture industries, horticulture centers, abattoirs, animal ranches, grasses, trees, and invasive and alien species	https://dffe.gov.za, accessed on 18 February 2022.
South African National Energy Development Institute	To produce bioenergy (e.g., woodgas, charcoal, biogas, biofuel) from renewable sources of energy, employment, enterprises, and skills development	Cooking, water heating, space heating for low cost housing, electricity generation, biofuels for rural applications, chemical industries, fertilizers	Agricultural waste, invasive alien plants, bush encroachment and grasses, and municipal solid waste	http://www.sanedi.org.za, accessed on 18 February 2022

Lomati Energy (Pty) Ltd. (in Barbeton, Mpumalanga) has produced 8.5 MWe of electricity and reduced annual carbon emissions to roughly 55 kilotons. The project activities involved installation of a biomass-based cogeneration plant intended to generate steam and electricity. Another wood-processing company, South African Pulp and Paper Industries Limited (SAPPI) (Johannesburg, South Africa), is building a biomass facility in Mpumalanga to generate 25 MW of electricity from wood scraps using a thermal method. Such initiatives attempted to improve electricity supply in the South African grid in order to safeguard future energy supply with the help of clean, carbon-neutral energy and combat climate change by utilizing waste materials such as sawdust, shavings, barks, and off-cuts, and now by using the biomass from invasive alien plants [6,42]. The initiative made a contribution to social issues such as by providing new job opportunities; for example, the biomass plant created about 344 jobs during the construction phase and 120 direct jobs during operational phases for the socio-economic development of the society. A 1.5% revenue during the operational phase was to be spent on socio-economic development, skills development, education, nutrition, and social welfare [42,49].

According to one estimate, South Africa will require a new power source of at least 29,000 MW by 2030. In addition, old Eskom power stations (with a capacity of 10,900 MW) would need to be retired during the same time period, and the country plans to have 19 GW of renewable energy capacity by 2030. This is an exceptional opportunity for South Africa's green energy sector to align the country's growth trajectory with sustainable development and climate change goals [4–6,14,40]. If this trajectory does not materialize then, South African energy will rely on unsustainable coal, which currently provides 85% of the country's energy and causes high greenhouse gas (GHG) emissions [39]. Indeed, South Africa is the highest GHG emitter in the continent and ranked the 12th-largest global emitter, with 434.5 Tg of CO_2 emitted in 2020 from fossil fuel combustion (i.e., oil, gas, and coal) [21,50]. Undoubtedly, the use of coal for power generation is not compatible with other leading edge energy technologies, in addition to being expensive, which invites threats to the economy.

3.4.2. Charcoal

South Africa is a significant producer of charcoal, which is obtained from the biomass of invasive alien plants through the Working for Water Programme [21]. Due to a monopoly and a grip of middlemen on the charcoal market and prices, a large number of charcoal producers in rural regions are employing invasive alien plants as feedstock. However, they are not receiving the intended benefits. Other factors include fierce market competition, high production costs, and transportation costs for biomass [6,21]. As a result, technological advancements are required to create and employ efficient kilns in order to produce competitive charcoal [15,21,51]. Furthermore, because charcoal is often used for social purposes in higher-income households, a decentralized market for charcoal is required [15]. On-site charcoal manufacture would result in uncontrolled fires, destroying biodiversity and contributing to regional air pollution [51]. As a result, a secure location is necessary for the building of efficient kilns for enhanced charcoal output that are effectively connected to the supply chain, logistics, and market [15]. In addition, the principles of biomass to bioenergy outlined by Karekezi et al. [51] must be addressed, including (i) certification of biomass sourced from sustainable resources (e.g., wood plantations and sustainable management of native forests), (ii) widespread dissemination of widely improved biomass energy technologies, and (iii) promotion of advanced biomass energy technologies for the production of high-quality energy.

3.4.3. Biochar for Soil Improvements and Conditioning

Biochar is gaining popularity as a climate change mitigation tool in the agriculture and forestry sectors around the world [44]. The carbonized residues left over from the power generation and charcoal production processes could be used to improve soil quality and as a soil conditioning agent. The fine particles of charcoal residue can be separated and packaged into plastic bags as organic manure for soil improvement, plant growth promotion, and soil micro-organism management. In agricultural areas and gardens, a modest amount of organic matter combined with charcoal promotes soil fertility [44,52]. The use of charcoal in soil creates a microhabitat in which AM fungus can colonize and thrive [53]. Furthermore, by boosting the soil's ability to absorb nutrients and agrochemicals, it enhances water quality and quantity, leading to greater agricultural output and improved food security and farmland diversity. Biochar's environmental benefits include carbon fixation and storage in the soil for hundreds to thousands of years.

3.4.4. Eco-Industry Hubs

Eco-industry hubs are critical for promoting invasive alien plants-derived value-added products [18]. The Working for Water Program has set up roughly five eco-furniture manufacturers across the country, including in George, Durban, Pretoria, Heidelburg, and Graskop, in order to use biomass from invasive alien plants clearing projects for the manufacturing of various value-added forest products, as well as to improve rural well-being and create jobs. There is a strong desire to work with the Department of Economic Development to build more factories across the country. These manufacturers produce school desks and benches, garden furniture (e.g., benches, direction boards, plant protection baskets, and bin boxes), dog kennels made from off-cuts, eco-coffins, and other value-added items, all of which are subject to Treasury approval.

According to reports, the country is short of seven million school desks. For example, the George plant can produce approximately 140 desks every day. Value-added products have been made from *Eucalyptus* spp., *Pinus* spp., and *Acacia melanoxylon*. The school desks are donated, mostly to schools and hostels in disadvantaged areas of the country. Similarly, dog kennels are available for donation to rural or informal settlements in order to shelter their pets from the elements throughout the winter and rainy seasons. The wood-processing residues and small pieces are being sold to the public for use as firewood and other uses at a low cost [18,46]. Furthermore, through apprenticeships, these firms have provided a great number of jobs and assisted in the development of skills in previously underprivileged communities [35]. Around 1700 employment opportunities have been created in the eco-furniture companies across the country, including in the harvesting and extraction processes of invasive alien plants. Such innovative use of invasive alien plants biomass contributes to inclusive development, social being development, job creation, biodiversity, and conservation of ecosystems services in the country [34,35].

3.4.5. Firewood

Firewood for Rural Communities

The majority of South Africa's rural population is poor, and they rely on low-cost biomass fuels, primarily firewood, for their daily heating and cooking needs. For reasons of price and distance from the grid electricity supply, it has been claimed that firewood would continue to be an essential energy source in rural areas for decades to come [15,54]. Overuse of firewood in rural areas has resulted in deforestation, posing a threat to ecosystems and the services they provide to human well-being [15,18,21], which requires attention both locally and nationally. As a result, there is a potential for novel applications of biomass created by WfW clearance initiatives.

Biomass from invasive alien plants, particularly firewood, can be supplied to rural households to conserve the natural forests, where 80% of rural households across South Africa are dependent on firewood as a primary source of energy [18,48,55,56]. This type of intervention could help to mitigate the deforestation problem in rural areas [15,57] of South Africa [56]. Petrie and Macqueen [48] reported that about 20% of urban households and a half of rural households are still off-grid. As a result, the intervention would considerably contribute to meeting the household needs of disadvantaged communities, reducing their reliance on adjacent forests, and thereby conserving the environment and alleviating forest degradation [15]. It will also save households time, money, and energy by reducing the amount of time, money, and energy they spend collecting firewood. Local communities should also be allowed to harvest invasive alien plants in their area, such as on the outskirts of Georgetown. Local impoverished populations living in squatters' camps have been given permission by certain private landowners in George to harvest invasive alien plants from their properties in order to get rid of invasive alien plants, decrease their impact, and control them as required by law. This kind of practice supports conservation via the strategy of utilization of invasive alien plant species for biodiversity conservation and environmental sustainability [30]; nevertheless, these schemes are controversial and have not been proven to be beneficial in the workplace. On the other hand, in locations where rural communities rely on invasive alien plants for firewood, there may be a scarcity of firewood [54].

Firewood for Urban Communities

It is clear that city inhabitants utilize firewood for space heating and braai. There are already some established informal firewood marketplaces and supply chains that harvest and transport wood from areas where there is sufficient or excess supply to areas where there is a scarcity. Biomass from invasive alien plants can be made more easily accessible to such supply chains [34,54]. These markets support a competitive firewood supply chain while also creating jobs in the area. There appear to be well-established firewood markets in both cities and towns. Because firewood is also utilized by middle- and higher-income people in towns and cities for braai and surface heating during winters, these marketplaces primarily sell wood from *Acacia* spp. However, such alternatives must be evaluated in light of the availability of adjacent biomass from invasive alien plants, as well as the competition from existing raw materials [35,48]. Nonetheless, even if a market exists locally, a proper legislative framework is required to ensure that the market is durable and productive. Furthermore, woody plant resources, particularly invasive alien plants, are utilized for a variety of uses in both low- and high-income suburbs of cities. Invasive alien plants are also used by newly forming and expanding informal settlements for firewood, fencing droppers, and building materials. The firewood is mostly used for cooking and heating the surface [55,57]. The fencing droppers are used to enclose homesteads, while the poles are used to construct low-cost houses.

Firewood for Farm Houses

Farm houses use firewood for surface heating and night fires [56]. Several communal functions are held at farm houses, including family reunions, wedding ceremonies, and night fires, and firewood is used for eco-tourism. The droppers are utilized as fencing at the farm houses in addition to providing firewood. Some landowners chip and compost the wood, while others simply chip and spread it on clearing areas to reduce fuel load and hence minimize the fire hazard [34,51]. The chips can be used to generate heat and steam directly. The black wattle stand in Woodifield Estates in George Town, for example, has been utilized for firewood and fencing droppers. As part of an invasive alien plants management approach, the landowner developed a small biomass plant to manufacture firewood for the local market and to generate a profit, which helped to cover the landowner's management costs. Interestingly, many of the landowners with whom discussion was held have said they had no idea how to deal with invasive alien plants growing on their farms [34]. Many of them want to compost the wood for use in vegetable gardens or sell it in order to manage invasive alien plants on private properties [52], thereby contributing to biodiversity conservation and environmental sustainability [30,34,35].

4. Existing and Emerging Challenges

4.1. Challenges Related to the Viability of the Market

Finding a suitable use for the significant amount of invasive alien plants biomass has been a long-standing local challenge that also presents a unique opportunity. If the biomass of invasive alien plants is utilized sustainably, it will result in green economic development and the environment sustainability [20]. About 97% of the commercial biomass of South Africa is extensively exported because of the lack of support for local markets [21]. Hence, adequate efforts should be exerted so that the products generated from invasive alien plant biomass are competitive both locally and internationally [6,18]. Cases like the Howick Wood Pellet Plant and Tstsikamma biomass plants failed due to a lack of suitable local market conditions [48]. Pellet manufacturers failed not just as a result of their inability to compete in the European market, but also as a result of their pricing being too high for local markets [6]. However, the scenario could be different if biomass is used as a fuel for the generation of power [37]. Abundant biomass originates from 42 million ha of natural woodlands, 1.35 million ha of plantations, and significant tree resources existing outside of forests, which offer an existing supply of 1.2 million tons of wood fuel [37]. As well as the untapped invasive alien plant biomass [34], these resources could enable the generation of clean and economically and environmentally competitive electric power. Furthermore, there is untapped feedstock derived from agricultural and garden wastes, which Eskom rarely uses. As a result, government support and incentives are required to keep biomass-to-power conversion plants afloat [4,5,48].

The failure of some of the aforementioned biomass plants implies that concerted initiatives and government incentives are needed to build local markets [48]. Failures can be used as lessons for progress in the energy sector. According to Petrie [21], sugarcane bagasse, timber-harvesting residues, sawmill residues, and pulp and paper mill residues have the potential to generate 5500 gigawatt hours (GWh), 2722 GWh, 2122 GWh, and 2542 GWh of electricity, respectively. However, no assessment of invasive alien plants' prospective capacity to generate GWh of energy has been undertaken [6]. Biomass gasifiers, which burned wood chips, were once widely employed in South Africa to power water pumping motors. Due to the use of generators powered by fossil fuels, particularly coal, most gasifiers were shut down in the 1960s [41]. According to Field et al. [58], biomass energy is dependent on four factors: (i) conversion technology and biomass to fuel conversion processes for increasing efficiency, (ii) biomass sources that can be used for bioenergy generation, (iii) land and water resources for biomass production, and (iv) biomass energy technologies' implications.

4.2. The Cost of Harvesting, Chipping, and Transport

Efficient equipment is needed to be developed for the harvesting of biomass from invasive alien plants [46]. Mugido et al. [16] reported that several factors, such as slope, distance, biomass, and riparian areas, can impact the value chain of biomass from invasive alien plants. Harvesting and extraction costs account for the majority of total production costs, followed by chipping and transportation. The overall cost of harvesting, extraction, bucking, chipping, and transport for *A. longifolia* was predicted to be highest, followed by the combined cost of *Eucalyptus* spp.–*Acacia* spp.–*Pinus* spp. The harvesting and extraction costs are estimated to be higher than chipping and transport costs for all species, both separately and in combination [16,17]. As a result, biomass plants must be built close to available biomass resources in order to reduce greenhouse gas (GHG) emissions from long-distance transportation, and to cut costs and prices [6,20]. South Africa is having difficulty utilizing and managing the biomass produced by invasive alien plants clearances [30]. The fact that biomass fuel for electricity generates little ash and emits few hazardous gases is a favorable environmental benefit [6,14,15]. The negative impact, on the other hand, includes the necessity for a long-term supply of high-quality biomass and the accompanying delivery costs. An incentive mechanism is, therefore, required for the development of the biomass energy market in South Africa, both for efficient wood pellet stove technologies and for electricity generated from biomass feedstock [6,8].

Transportation is costly due to the remoteness of biomass gathering sites [6,16]. *A. longifolia* has the highest transportation costs, followed by a combination stand of tree associations of *Eucalyptus* spp.–*Acacia* spp.–*Pinus* spp. The costs of harvesting/extraction were discovered to be between ZAR 200 and ZAR 400 per Wet ton. The harvesting expenses ranged from ZAR 176 per wet ton to ZAR 1160 per wet ton. The transport expenses were around ZAR 152 per wet ton, with a minimum cost of ZAR 113 per wet ton and a maximum cost of ZAR 207 per wet ton [16]. If the biomass installations are located far from the road network, the cost becomes considerably higher than when coal is used [16]. Costs are reduced with an efficient transportation infrastructure and trained labor. Transportation accounts for the largest portion of all cost components [6]. Therefore, it must be significantly decreased, which would also reduce greenhouse gas (GHG) emissions [14,20].

4.3. Sustainable Green Jobs and Skilled Labour

Lack of skills has resulted in a high unemployment rate in South Africa, particularly in the country's underprivileged rural populations [41]. The development of ten jobs for unemployed people educated as gasifier operators in Melani village, Eastern Cape, South Africa, is a good example of the beneficial social impact that biomass-to-energy initiatives may have [4,5]. Mamphweli and Meyer [41] also stated that community members interested in the program require skills development for modest to large business initiatives. Such projects generate a growing number of job openings [6,15]. The majority of individuals in rural areas are unemployed and unskilled, and they could benefit from the implementation of a similar bioenergy scheme. Several people can be hired as gasifier operators, artisans, saw operators, and general employees as a result of this. In fact, clearing of invasive alien plants is a labor-intensive activity that can provide a substantial number of jobs in rural regions [30] and encourage bioenergy, if implemented correctly and sustainably [6,15]. Previously, failing pellet facilities in Howick employed roughly 72 people on a permanent basis [21]. If the bioenergy sector receives governmental support, it has the potential to produce a substantial number of jobs, contribute to the bio-economy, and provide competitive green energy. Despite the fact that renewable energy technologies are still in their infancy in South Africa [59], the country's already existing biomass plants and eco-furniture industries employ a large number of people and are constantly improving the requisite capacity and skills for green economic development and industrial transformation.

5. Policy Responses

New legislation, such as the National Environment Management: Biodiversity Act (Act 10 of 2004) (NEM:BA) and the National Environment Management: Protected Areas Act (Act 57 of 2003) (referred to as the Protected Areas Act), impose responsibilities and obligations to eradicate, control, and manage invasive alien plants. The act divides invasive alien plants into different categories based on their severity and the activities that must be taken to contain them [35]. Category 1-invader plants, for example, must be uprooted and destroyed right away (with 1a requiring compulsory control and 1b requiring management-based control), category 2-invader plants may only be cultivated under limited conditions, and category 3-invader plants cannot be planted at all [60,61]. By 2014, 559 invasive alien species had been identified for management, including 383 plant species [30]. As a result, the WfW Program is widely accepted across the country for controlling, managing, and eradicating invasive alien plants on both public and private areas. The South African Environmental Observation Network lists invasive alien plant species as one of the bioenergy sources (SAEON). They believe that biomass from invasive alien plants clearings could be an excellent bioenergy feedstock [16,17]; the issue is the remoteness of biomass collecting sites and the high cost of transportation from harvesting sites to marketplaces and processing sites [6,16].

The South African government has now conceived the Working for Energy initiative to use the invasive alien plant biomass generated through the WfW Program for bioenergy and rural well-being development through employment and provision of energy (SANEDI; URL: http://www.sanedi.org.za, accessed on 18 February 2022); https://www.environment.gov.za, accessed on 18 February 2022). Despite this, Working for Energy is also considered an innovative approach to create green jobs and reduce GHG emissions [4,5,35,46]. Previously, the policies have not made the sector attractive for investors [62]. Hence, South Africa's energy strategy aims to increase the energy contribution, environmental sustainability, green job development, and poverty reduction [6,15,42]. In doing so, policy instruments like these are critical for South Africa's energy-intensive economy. Energy efficiency and demands must be taken into account when planning for energy pricing, population expansion, environmental and social sustainability, sustainable forest resources management, sustainable forestry, safeguarding biodiversity, and ecosystem services for green economic development and industrial transformation [4,5,46]. South Africa must also align its research and energy policies in order to fulfill the existing and future energy demand for green economic growth and industrial transformation [43].

Energy policies are developed and implemented by a diverse group of government departments and agencies. Although the cost of using biomass for energy is currently high, it could be reduced through time [6]. To meet the sustainability goals, it must concentrate on renewable energy sources [14,15,34]. As a result, the South African government has launched a biomass-to-energy effort aiming at producing various forms of bioenergy in a sustainable manner, while also supporting poverty alleviation, green job creation, and skill development (Table 1). The current study is aligned with South Africa's National Development Plan 2030, particularly the aspects of the bio-economy and green energy development. The various sources of energy would be harnessed for many applications, such as cooking, water heating, space heating, industrial heating and processing, electricity generation, biofuels for rural applications, and in chemical industries and fertilizer processing. The biomass-to-energy program also has a social component, such as rural well-being development and sustainable livelihoods, with a particular focus on youth, women, and people with disabilities in rural areas and low-income urban populations. The scope and outcome of this study would be that, if biomass from invasive alien plant clearing projects is utilized with due consideration of costs and benefits (for the bio-economy, green energy, and forest product development), then it would help improve energy efficiency and wood waste management, and support climate change mitigation, thereby contributing to green economic development, biodiversity, and protection of ecosystem services [4–6,14,19,25,35,42].

6. Conclusions

There is a need to develop an adequate policy framework and incentive program to use biomass for bioenergy and other value-added products. This study suggests that options for screening of priority products (e.g., electricity, biomass pellets, and value-added products) and biomass for industrial feedstock (e.g., species and energy values) are required. Site-specific small and medium-sized industries, such as chicken and dairy farms, could benefit from the generated thermal and electrical energy. The modern bioenergy system needs to be advanced to meet increasing future energy demand and the use of biomass from invasive alien plants for green economic development, sustainable forest management, and safeguarding biodiversity and ecosystem services in the country. It is critical to maximize the benefits of invasive alien plant biomass use in both the domestic and industrial sectors. Biomass from invasive alien plants needs to have specific and assigned depots or purchasing places nationwide, where landowners could bring their wood or biomass for sale. Being participatory, such an approach would save a large amount of expenditure on clearings, management, and developing schemes for green economic growth, green energy, industrial transformation, and environmental sustainability.

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