Paradox of Deadwood Circular Bioeconomy in Kenya’s Public Forests

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Abstract: With the rising demand for energy, the forest-based circular bioeconomy is gaining recognition as a strategy for sustainable production and consumption of forest resources. However, the forest-based bioeconomy remains underexplored from the perspective of deadwood conservation in public forests. While conducting a literature review and examining the case of Kenya, this study fills a gap in the literature to provide policy suggestions for sustainable forest resource utilization. The results from global literature indicate that deadwood performs essential social, economic, and environmental functions in the circular bioeconomy and sustainable development. Similarly, in Kenya, deadwood resources provide many socially beneficial bioproducts and services. However, the absence of scientific research and detailed guidelines for deadwood conservation may lead to the distortion of the ecological balance in public forests because of the legally sanctioned removal of deadwood, particularly firewood. Moreover, if the status quo remains, with approximately 70% of the growing population consuming deadwood for domestic use and the demand increasing, as shown by the current wood deficit in the country, there will be a major dilemma concerning whether to conserve deadwood for biodiversity or energy. Therefore, averting crisis and providing maximum deadwood value to society requires guidelines and comprehensive research in addition to a cultural and behavioral shift in energy consumption in a manner that embraces the forest-based circular bioeconomy of deadwood.

Keywords: deadwood; bioenergy; biodiversity loss; sustainable development; efficiency; energy mix; renewable energy

1. Introduction

Unsustainable human activities, especially the production and consumption of energy resources from biomass, are exacerbating climate change, loss of biodiversity, and pollution. This is increasingly upsetting the balance between the environment, society, and economy [1,2]. Moreover, the growing population and rising urbanization are exerting additional pressure on the environment, thus compounding the existential threats facing humanity. Public forests constitute a panacea for these threats, provided that all their components, especially deadwood, are sustainably managed [3,4].

Deadwood, in this paper, refers to dead or dying trees, carbon pools in stumps, heartwood, and other tree biomass parts, and as found on the forest floor or in the canopy of trees [5–8]. Deadwood in public forests provides many ecosystem services (provisioning, regulating supporting, spiritual, and cultural) that benefit many types of flora and fauna, including humans, in the course of sustainable development. In this respect, empirical studies show that deadwood generates high biodiversity on the forest floor, which is needed for achieving and maintaining the global ecological balance [9–11]. Consequently, robust and sustainable policies are increasingly being developed to raise public awareness and consciousness of the importance of deadwood resources in public forests.

However, the conservation of deadwood remains a highly contested environmental issue. Key forest actors are strongly divided as to whether deadwood in public forests should...
be conserved for biological diversity conservation or should be exploited for bioenergy resources. These arguments have surfaced from an ongoing debate showing that some topics related to biodiversity have failed to attract attention. For instance, some groups of organisms related to deadwood resources—such as fungi, micro fauna, and bacteria—are typically overlooked by many people, including some foresters and key environmentalists. From the perspective of their extrinsic value, these organisms usually associated with deadwood are considered insignificant. This study notes these oversights and emphasizes that the determination of an organism’s relative importance should consider both the extrinsic and intrinsic values associated with it. This value attribution makes it possible to appreciate biodiversity associated with deadwood and its ecosystem benefits based on their total economic value, which currently dominates conservation circles. Fortunately, this consciousness is rapidly growing with an equally increasing level of awareness of deadwood biodiversity amongst forest decision makers. In fact, because of these awareness levels, the focus on the sustainability of deadwood resources is changing to incorporate new and emerging concepts such as the forest-based bioeconomy [12]. In a forest-based bioeconomy, all forest resources are exploited for maximum value based on the available scientific knowledge with an emphasis on improving the quality of life. A bio-based economy built on forest resources, for example, deadwood, fundamentally aims to change the existing production paradigms, which appear mainly fossils-based, to a highly integrated and closed production system where innovation and dialogue between industry and community actors are harnessed to develop the best solutions and bio-based policies. Moreover, efforts are being made to adopt strong and more robust forest-based bioeconomy policies that link the entire forest value chain right from the management and use of resources in the delivery of forest goods and services. The best policies and interventions in the case of deadwood are increasingly highlighting the need for sustainability by enhancing the differentiation between the economies of scale in bioenergy value chains, the economies of scope in biotechnological valorization pathways, and sustainable business models and bioeconomy systems. These policy improvements have been associated with increasing interest in forest resources, for instance, increasing demand for various goods and services, including ecosystem services, which, in turn, improves the economic potential of the sector [13].

Contrariwise, in Kenya, there is a lack of adequate data and information on the utilization of deadwood in public forests. Additionally, there is limited awareness of how public policy on forest management could be improved to create positive synergistic effects with deadwood from the perspective of a circular forest-based bioeconomy. Thus, this study seeks to address this challenge by reviewing the status of deadwood in Kenya’s public forests. In pursuit of this goal, Kenya’s public forest development matrices will be explored for the first time to draw key lessons by answering the following questions: (1) Is deadwood in public forests more important for biodiversity conservation or production of bioenergy in Kenya? (2) How can forest policies on deadwood be improved to promote a forest-based bioeconomy in Kenya? This study has chosen Kenya as the case of study because it is one of the few African countries where a bioeconomy strategy is being developed, but studies appear to show that the country is still ranked as a low-forest-cover country that is under the constant threats of environmental challenges. Moreover, despite the country having vast renewable energy resources, many households still face significant energy access challenges. In this regard, exploring the contextual information for Kenya and the policy options for sustainable deadwood management can reveal information that is of interest to researchers and policy makers.

The current forest landscape in Kenya and circumstances explaining the sector’s instability are fluidic. Between 1990 and 2000, the forest sector experienced unprecedented pressures, with a notable reduction in forest cover occasioned by erratic and ad hoc decisions. Nevertheless, Kenya’s Vision 2030 presents a good opportunity for accelerating the forest sector’s contribution towards transforming into a middle-income country. Vision 2030 is founded on three bases: political, economic, and social. These pillars are further grounded in energy, science, technology, innovation, infrastructure, security, public
sector reforms, macroeconomic stability, land reforms, human resource development, enhanced equity and wealth creation, and continuity of governance. In this study, we will explore the energy dimension focusing on understanding Kenya’s options to promote the sustainability of deadwood in public forests.

Kenya is a multi-party democracy in East Africa. The country has a decentralized governance system composed of 47 counties (devolved units). After attaining its independence in 1963, Kenya realized several social-economic achievements. Currently, Kenya’s population is 47 million people with 12 million households with an average household size of 3.9. According to projections, the number of people will increase by 2.2% per year. Kenya’s population is set to reach 60 million by 2030, with urban residents making up half of the population by 2027. The population density is 82 persons/km² [14]. Counties or devolved units in the central and western parts of the country have higher population densities than those in the eastern and northeastern parts of the country. The annual housing demand is estimated at 250,000 units and appears to be rising with the growing population. The poverty rate stands at 36.8%, with a 2.65% unemployment rate reported in 2020. The highlighted socio-economic matrices indicate that Kenya will likely consume more energy in both domestic and industrial use during its transformation in line with Vision 2030.

At the national level, biomass energy constitutes approximately 68% of energy consumption, with petroleum usage standing at 22%, electricity consumption 9%, and coal 1%. Electricity was predicted to replace biomass and wood fuel consumption for most Kenyans. However, it remains underexploited due to the increasing costs of electricity in the country. For example, according to the Global Oil Price Website [15], the electricity price for households in Kenya, as of June 2020, was USD 0.201, compared with Venezuela’s USD 0.000, Sudan’s USD 0.001, and Ethiopia’s USD 0.009. Biomass energy contributes approximately 83% of the total energy consumption in major economic sectors (agriculture, transport, and commerce), while petroleum contributes approximately 17% to transportation and commerce. Kenya’s electricity generation by source and total primary energy consumption by the source is largely dominated by geothermal (44%), hydro (33%), thermal (11%), wind (10%), solar (1%), and imports (1%). Biomass makes up the largest proportion, with biofuels and wastes accounting for 68%, followed by oil (25%), electricity (4%), and coal (3%) [16,17]. Thus, Kenya’s energy mix is strongly dominated by traditional biomass, which accounts for more than half of the country’s total energy consumption. The high biomass proportion is attributed to households’ use of wood as a source of energy, particularly firewood (deadwood), for cooking and heating. Moreover, agricultural expansion and population growth create a 20-million-ton shortfall per year in fuelwood supply, further aggravating deforestation, drought, desertification, famine, land degradation, and illegal practices related to fuelwood extraction. Interestingly, Kenya is also a viable commercial market in the East African Region for solar power products and other forms of renewable energy resources, with indications of steady investments in solar power in the period 2010–2015 [18]. Given the rising interest in solar power and related technologies, the country is developing guidelines for sustainable solar power utilization [19]. Additionally, the country revised its carbon emission targets from 30 to 32%, focusing on promoting renewable energy sources [20]. However, based on previous findings on national energy consumption, the energy demand continues to grow at the rate of 2.5% annually [21,22]. In addition, major deficits are anticipated in the household and cottage industry, with a biomass shortfall of over 20 million tons, if significant policy measures are not implemented; hence, this study is essential in the present context.

2. Circular Forest-Based Bioeconomy and Deadwood Management Strategies

Forests provide numerous ecosystem services that significantly contribute to attaining and maintaining a complex ecological balance amongst lifeforms on the planet [23]. These ecosystem services have a significant “safety net” and “gap-filling” role for many lifeforms, including animals and humans. For instance, in the case of humans, forests provide compounds that are used in pharmaceuticals and nutraceuticals [24,25]. Mushrooms and
various fungi extracted from forests have been found to possess invaluable pharmacological potential [26,27]. In addition, forest food can provide nutrients that people may not have access to and may help people survive famine, war, or drought [28–32].

Furthermore, naturally, forests, including public forests, are characterized by natural tree death, which leads to the accumulation of diverse deadwood on the forest floor. Deadwood biomass and structures provide many ecosystem services that support the interaction and livelihood of different lifeforms within a forest to create ecological balance. For instance, existing literature shows that many deadwood-dependent lifeforms are found in habitats created by deadwood crevices and cavities [33,34]. Deadwood reserves can contribute to long-term soil organic carbon enhancement of forest floors in dependence, e.g., the abundance and presence of nitrogen-fixing bacteria [34]. Some types of insects require the occurrence of a certain type and diversity of fungal species, which are, in turn, associated with certain types of deadwood. In addition, Kortmann et al. [35] found that deadwood can promote the availability of food resources at higher trophic levels. Considering this connection, studies such as Tillon et al. [36] established a higher bat diversity in forests with high amounts of deadwood. Lindenmayer and Ough [37] and Jaroszewicz et al. [38] established that deadwood, including old trees, provide roosting sites, nesting, hibernation sites, and shelter for many forest lifeforms. This empirical evidence illustrates the value of deadwood for biodiversity, the dependence of insects’ populations, and thus stable insect biomass supply for bird populations and other vertebrates. Hence, the need for sustainable management of deadwood resources. However, the lack of data on distribution and decay rates of deadwood appears to be complicating the chances of sustainably managing deadwood resources.

Historically, deadwood conservation was institutionalized from the mid-1990s with a series of discussions in North America and Europe, leading to the creation of deadwood-specific sustainability indicators [39]. Despite these efforts, existing literature shows that the thresholds for prioritizing deadwood resources vary in different countries depending on the deadwood policies adopted. For instance, previous research demonstrates that there are many initiatives in European forests to create and increase the amount of deadwood on the forest floor. Unfortunately, the growth of deadwood is not always based on biological diversity considerations because, in terms of biodiversity, many European forests remain below the optimal levels [39]. Nonetheless, the management of deadwood in public forests around the world remains challenging and context-based because deadwood may not always be popular to the public due to the lack of appealing characteristics [40–42]. Moreover, forest degradation caused by the legally sanctioned removal of deadwood continues to challenge many forest actors, including key policy makers around the globe [43–49].

Fortunately, emerging forest management concepts, such as the circular forest-based bioeconomy, seem to be gaining recognition in forest management discourses and might help to alleviate the challenges of deadwood management. A circular forest-based bioeconomy of deadwood resources refers to the totality of activities that entail converting deadwood into various product streams, including materials, chemicals, biofuels, food, and animal feed, and many ecosystem services provided in healthy forest ecosystems [50–57]. The forest-based bioeconomy of deadwood resources can be successful if production and consumption patterns are transformed to increase energy and material efficiency. This transformation can further benefit from existing technological opportunities, such as biotechnology, and societal desire to transition to clean production systems, eventually generating new materials and renewable energies. In the context of deadwood, a circular bioeconomy aims to increase sustainable reliance on deadwood resources with improved efficiency in resource use and circular material loops. Historically, the concept of a circular bioeconomy originated in Europe to address the industrial consequences of biological advancements that require the economical use of biotechnologies and the replacement of fossil fuel-based resources for energy and material use. Over time, due to global environmental crises, the bioeconomy developed into a global concept, which involves using the knowledge from biological sciences to create economic activity and public benefit in both developed and developing
countries. Malaysia and South Africa released their bioeconomy policies in 2013. Many industrialized countries had already adopted bioeconomy policies and strategies before the year 2013 [58,59]. North and South America, Asia, Australia, and Europe are steadily moving toward dedicated bioeconomy strategies, while the African continent appears to be lagging [59]. Nonetheless, the bioeconomy continues to attract a considerable amount of interest and has a relationship with associated concepts such as the green economy. It is hoped that the development and implementation of these bioeconomy policies and strategies will consider deadwood resources in view of their use and non-use values.

Successful integration of deadwood resources in a circular forest-based bioeconomy in a country requires that certain critical factors are examined. Existing literature indicates that a country’s competitive advantage in developing its bioeconomy policies and strategies is determined by four elements or pre-conditions: factor conditions; demand conditions; firm structure; rivalry; related supporting industries [60]. However, the conditions that promote bioeconomy can be typically classified into the following: First, the natural conditions emphasizing a country’s natural endowments and favorable agro-climatic conditions show competitive advantages for a biomass-based bioeconomy. Countries with low population density, favorable agro-climatic conditions, and land endowments are in an advantageous position to pursue the resource substitution perspective of bioeconomy and have the potential to produce bioenergy and bio-based products on a large scale at comparatively low costs. Contrariwise, countries with less favorable natural resource conditions can focus more on biotechnology perspectives. Second, labor resources are important for bioeconomy development since it requires a unique skill set. Therefore, to improve its labor resources, a country must invest in bioeconomy-specific education programs. Third, the bioeconomy requires knowledge resources established through research. Thus, governments must create conducive conditions for research by private-sector institutions. Fourth, investments in capital resources along the entire value chain of products are also necessary. Finally, adequate infrastructure is required to support the bioeconomy, particularly in terms of transport and information and communication technology, which could help improve the demand for bio-based products [61]. As the global population grows, many countries are increasingly recognizing the value of deadwood resources, as evidenced by the growing body of scientific knowledge. Countries are likely to establish the requisite infrastructure and labor resources that will support the sustainable utilization of deadwood in anticipation of the accompanying sustainable development gains.

However, in practice, existing bioeconomy policies and strategies vary amongst countries in the context of themes, drivers, and areas of focus. For instance, many European countries have considerably advanced bioeconomy policies and strategies promoting economic activities based on the available knowledge of biological resources. In European parlance, the cumulative representation of these economic activities has been termed “the photosynthesis economy.” Table 1 shows a summary of the broad bioeconomy strategies in four European countries. Addressing climate change may be the primary focus area of a circular bioeconomy in these countries, along with the need for environmental sustainability. Overall, in view of the values attached to deadwood, these bioeconomy attributes indicate the possibilities of further integrating the management of deadwood resources in existing economy-wide bioeconomy policies, including those targeting the sustainable management of forest resources.

Moreover, across all bioeconomy strategies shown in Table 1, the key strategy ingredients include the following: application of innovation, integration of strategy in the digital economy, the importance of forests in strategy implementation, and the importance of education, research, and training. However, the sustainability of biomass resources, social issues, and, in particular, the mechanisms of public participation in the strategy and policy implementation appear to be unclear [61]. Additionally, the strategies have been criticized for their fragmentary consideration of the necessary framework conditions and lack of transformational ambitions and an appropriate definition of sustainability [61,62].

Exploring the forest-based circular bioeconomy in the context of deadwood and related concepts such as green economy is essential because the relationship between society,
environment, and economic development processes has to be balanced. Studies report that many environmental problems are increasingly arising because of unsustainable development associated with the endless pursuit of energy resources, some of which tend to occur in areas with high biological diversity. Thus, if these projects are unsustainably implemented, it could escalate global environmental pandemics. Fortunately, the scientific community has been monitoring and mapping areas considered to be sensitive environmental conservation hotspots with a focus on determining which species are rare, threatened, or endangered under the auspices of the International Union for Conservation of Nature (IUCN) [62,63]. These efforts have helped identify species-specific ecotones that require urgent conservation. According to observations, a match seems to exist between the identified conservation hotspots and efforts to entrench circular bioeconomy policies where deadwood resources are also considered.

### Table 1. Bioeconomy policies in selected European countries.

| Strategy Name                                      | Theme                                      | Drivers and Focus                                                                 |
|---------------------------------------------------|--------------------------------------------|-----------------------------------------------------------------------------------|
| Bioeconomy strategy for France (2017)              | Promotion of the photosynthesis economy    | Implement climate change Agreement reached at COP 21                              |
|                                                   |                                            | Address the growing demand for proteins                                           |
|                                                   |                                            | Create more value chains for existing bioproducts                                |
| Bioeconomy in Italy (2017)                        | Reconnecting economy, society, and the environment | Reduce dependency on fossil fuels through a circular approach                     |
| Portugal’s green growth commitment (2014)         | Environmental sustainability               | Climate change                                                                    |
| Spanish Strategy on Bioeconomy 2030               | Sustainability                             | Change global consumption patterns                                                |
|                                                   |                                            | Climate change                                                                    |
|                                                   |                                            | Improving competitiveness                                                         |

Source: Authors’ compilations from [61].

Globally, the goal to associate the circular bioeconomy with the green economy has led to the development of bioeconomy concepts such as the biomass-based value web, suggesting that the cascading utilization of biomass and byproducts from processing creates an interconnection of value chains that are examined as interlinked value webs [64,65]. For example, Brazil appears quite advanced in its implementation of circular bioeconomy policies on biomass resources. In this context, Scheiterle et al. [65] presented an example of the biomass-based value web for the sugar cane sector wherein byproducts from sugarcane enable the generation of more such bioproducts instead of being disposed of as waste. Similarly, deadwood created in public forests in complex anthropogenic and natural ways can be harnessed through biotechnological applications to produce bioproducts essential for sustainable development. Anthropogenic activities create deadwood in forests worldwide, albeit with catastrophic consequences for biodiversity. Studies show that between 1970 and 2016, the planet lost many lifeforms, with a significant proportion now extinct [66,67]. Hochkirch et al. [68] concurs with the above findings and warns of an impending environmental catastrophe if biodiversity loss is not mitigated. However, the study notes that there have been few achievements in scientifically documenting the different lifeforms on the planet. On this note, in addition to more biodiversity studies, Hochkirch et al. [68] and Lassauce et al. [69] call for increasing environmental conservation measures for all lifeforms. However, to enhance planetary conservation, a shift is required in cultural and human behavior to support the circular bioeconomy of deadwood resources, which will sufficiently support the protection of biodiversity, extract maximum value from deadwood resources, and promote sustainable development.

Two broad forest management approaches have significant complementarity with the circular forest-based bioeconomy of deadwood. They are active and passive enrichment, where active enrichment entails human intervention in creating deadwood, whereas passive enrichment entails non-human interventions in the creation of deadwood [70]. However, the varying socio-economic interests for wood in different countries influence the application of these management approaches. Otherwise, protected forests without
human interference are more desirable for promoting the circular bioeconomy of deadwood [70]. Passive management of deadwood is important in implementing forest-based bioeconomy policies and strategies targeting non-consumptive ecosystem services, such as climate amelioration, regulation of pandemics, and supporting processes, including nutrient recycling and soil formation. Other active deadwood manipulation strategies include applying artificial mechanisms, such as roguing tree crowns and using explosives [70]. Other forest management strategies relevant to the circular bioeconomy of deadwood are outlined in Table 2. This study observes that the first three approaches (Table 2) support the conservation of deadwood biological diversity because natural regeneration is applied while causing minimal anthropogenic disturbances to the forest. However, depending on the context of implementation, these forest management approaches could promote the sustainable use of deadwood resources only after the context has been carefully evaluated. Therefore, it will be interesting to investigate the current deadwood management approach in Kenya and make policy recommendations on how a forest-based circular bioeconomy of deadwood could be explored.

Unfortunately, given the complex nature of deadwood caused by differing rates of decomposition, estimating the amount of deadwood that should be removed or created in a hectare of a forest in these forest management approaches is a challenging task. It complicates the sustainability of the forest-based bioeconomy of deadwood resources and the value chains to be derived. Moreover, a bio-based economy develops within the limits of the biosphere. Although biomass can be refined into many bio-based products, the sustainable provision of feedstock is limited to the annual growth of global biomass and the quality of biocapacity. In addition, the global distribution of biomass, including deadwood, is quite different, and there appear to be large regional differences in terms of volume of biomass such as deadwood, its quality, and the existing opportunities to adequately respond to the prevailing demand of bio-based products. In general, the existing literature on deadwood indicates that the available volumes are declining. As such, the overall effectiveness of the utilization of deadwood should be considered when designing policies. Therefore, when differentiating between bioenergy production and valorization pathways and the conservation of deadwood resources, the differentiation between economies of scale in bioenergy value chains and economies of scope in the case of biotechnological valorization pathways and nature protection businesses for sustainable deadwood use and conservation is of major importance. This differentiation should be aligned with the different life cycle stages of biogenic energy carriers from harvesting to conditioning and energy production and the value-added products and services derived from the intelligent valorization of deadwood resources, e.g., enzymatic products, pharmaceutical products, or nature protection marketing, for instance, of key insects when organizing park rallies. In addition, when differentiation is intelligently applied, both active and passive manipulation strategies for deadwood resources may provide vast opportunities for exploring a forest-based bioeconomy of deadwood resources [71]. Deadwood from public forests can produce many bio-based products in the form of wood fuel and related products. Wood fuels from deadwood can be classified into liquid, solid, and gaseous forms. Examples of solid fuels include chips, sawdust, pellets, and charcoal. Liquid fuels, on the other hand, may include black liquor, methanol, and pyrolytic oil, and gas wood fuel may include syngas [72]. To derive these fuel types and related bioproducts, many wood conversion technologies, and biotechnological applications exist that have ensured that wood, including deadwood, remains competitive [72]. These technologies include direct combustion, advanced direct combustion, carbonization, gasification, and extraction where liquid fuels—such as biodiesel, ethanol, bio-oil, and methanol—could be extracted by biotechnological methods, such as pyrolysis, fermentation and biorefining, cogeneration, and co-firing [73,74]. Considering the relative advantages of wood fuel, efforts to establish a forest-based bioeconomy have created a wood and wood-waste value web with significant potential for producing many bioeconomy products that are needed for sustainable development.
Table 2. Forest management approaches affecting deadwood in public forests.

| Forest Management Approach | Naturalness          | Tree Improvement                                      | Type of Regeneration                | Integration of Nature Protection | Tree Removal       | Final Harvest                          | Maturity                        |
|----------------------------|----------------------|------------------------------------------------------|------------------------------------|----------------------------------|-------------------|---------------------------------------|---------------------------------|
| Passive Unmanaged Nature Reserve | Natural Vegetation | None                                                  | Natural regeneration/succession    | High                             | None              | None                                  | No Intervention                 |
| Low Close to Nature Forestry | Native Site Adapted  | No genetic modification or Tree Breeding              | Natural regeneration or planting   | High                             | Stem              | Single stem, or group selection, irregular shelter-wood | Long rotation (MAI)             |
| Medium Combined Objective Forestry | Tree Species Suitable for Site | Planting Material from Tree Breeding but not genetically modified | Natural regeneration, planting, and seeding | High                             | Stem and crown    | All possible seed tree, strip, or group shelter-wood | Long rotation (MAI)             |
| High Intensive Even-aged Forestry | Tree Species Suitable for Site | Tree breeding allowed, no genetic modification | Natural regeneration, planting, and seeding | Medium                           | Whole tree        | All possible clear-cut, long rotation preferable | Short Rotation (Financial rotation) |
| Intensive Short Rotation Forestry | Any Species         | Tree breeding and genetic modification used           | Planting, seeding, and coppicing   | Low                              | Whole tree and residuals | All possible (Coppice clear-cut) | Short Rotation (Financial rotation) |

Source: [70].
Additionally, the wood-based bioeconomy is based on the concept of whole tree utilization, wherein new revenue streams and value chains are created during the processing of a tree in the downstream stages. Deadwood and biomass waste value chains can also be established, focusing on value addition. According to the existing literature, in a typical forest-based bioeconomy of wood, including deadwood, the lowest value is attached to using wood for energy generation to produce fuels, electricity, and heat. Contrariwise, the highest value is attached to the production of goods and services promoting health and lifestyle, such as pharmaceuticals and fine chemicals. Other products obtained from the cascading use of wood include food and feed, fertilizers, bulk chemicals, and commodities [74]. These products could have far-reaching implications for sustainable development. For instance, local communities relying on these products could easily transform into eco-communities. In developed countries with large urban areas with fewer deadwood resources, small urban biorefineries could be developed where communally generated deadwood could be utilized in the integrated generation of commodities. Rural areas with a high concentration of deadwood could become specialized in integrated large-scale production of products that require high-value addition, such as pharmaceutical, cosmetics, and other engineered bio-based products. However, more studies need to be conducted on the application of forest value webs to deadwood as a subset of the forest-based bioeconomy.

Some countries like Finland present excellent examples of how deadwood could be harnessed in a circular forest-based bioeconomy with many sustainable development benefits that could improve the quality of life in many developing countries. According to the Climate News website [75], scientists in Finland believe that deadwood can be turned into cheap biofuels through pressurized fluidized gasification technology. This can be used to deliver commercial quantities of bioeconomy products such as methanol with significant efficiency gains, energy security gains, cost reductions per megawatt-hour of energy, and reduced air pollution. For example, in the case of biotechnological application involving fluidized gasification, biorefineries for deadwood with 300 MW could produce energy bioproducts with huge cost savings [75]. Chile in South America provides a good example of how biotechnological applications for deadwood could promote socio-economic development by creating unique value chains. Using a special kind of decay process, wood is transformed into animal feed called "palo padrido" which is at an intermediary stage between the partial decomposition of the lignin and colloids, which results in the mineralization of wood. The process of transformation involves the isolation of a kind of white rot (fungi) that attacks the tree trunks of certain tree species and integrating their cellulose decomposition abilities with other forms of fungi and fermenting bacteria [76]. Deadwood resources can also be converted and used as charcoal through various carbonization systems, including systems with internal or external sources of heat required for drying and heating wood. However, despite the socio-economic benefits of charcoal production (Table 3), most charcoal production technologies in tropical countries, including traditional earth and pit kiln, have low wood conversion rates of approximately 20%. Thus, in the tropics, including Africa, charcoal production is considered to have the propensity to escalate deforestation in the absence of multi-stakeholder engagement and adherence to globally recognized principles of environmental sustainability, such as the forest-based circular bioeconomy [77,78]. Many deadwood products, particularly fuelwood, have immensely contributed to socio-economic development by generating employment. Biomass and deadwood conversion to byproducts is labor-intensive. It can generate more employment opportunities in the successive value chain activities, thereby reducing poverty compared with imported fossils, which exhaust the foreign currency reserves.

In Pakistan, it is estimated that over 600,000 jobs are created in the charcoal value chain, whereas in India, between 3 and 4 million jobs are created from the deadwood value chain [78]. Table 3 highlights the employment effects of various biomass energy sources, including deadwood resources contributing significantly to global socio-economic transformation. In this context, it is important to explore Kenya’s case and share lessons on the social effects of the circular bioeconomy of deadwood resources.
Table 3. Types of energy and employment effects.

| Fuel Type | Amount of Fuel per Terajoule (TJ) | Employment per TJ in Person Days |
|-----------|----------------------------------|----------------------------------|
| Fuelwood  | 62                               | 100–700                          |
| Charcoal  | 33                               | 200–350                          |
| Coal      | 43                               | 20–40                            |
| Kerosene  | 29                               | 10                               |
| LPG       | 22                               | 10–20                            |
| Electricity | 228 MWh                         | 80–100                           |

Source: [78].

However, the prolonged use of wood fuel and other deadwood products tends to escalate environmental problems, such as pollution and health complications among humans. The continued use of traditional biomass stoves produces harmful toxins that affect the users’ health, particularly women, children, and the elderly [79]. Rothman et al. [80] reported that in most developing countries, these people are at the highest risk of developing health complications due to continued exposure to in-door pollution [79]. In Gazi Bay in Kenya’s coastal forests, Jung and Huxham [80] found that a species of mangroves (Rhizophora mucronata) constituted up to 10% of the firewood used; additionally, people spent many hours collecting firewood. Chronic health impacts related to this fuelwood use were also reported [80]. These findings present challenges for the forest-based bioeconomy and associated strategies because most bioeconomy policies are still limited in some respects. Moreover, there are criticisms related to the alleged neo-liberalization of nature and misusing the label “bio” where a non-sustainable commercial system could easily be classified as environmentally friendly [81,82]. However, as product market and wood conversion technologies evolve, the continuous sensitization of the public to the benefits of a forest-based circular bioeconomy could help alleviate these challenges and hence the need for this study. Moreover, it is important to note that the forest bio-based economy is a paradigm shift rather than a material shift. It is a societal change of production systems to more integrated local production with more closed material cycles. To identify the best approaches at a system level, comprehensive bio-based product life cycle assessments are required to provide sustainable business models. It is also imperative that governments develop national programs, using policies, funding, and business ecosystems, which support economic stakeholders such as bioenergy operators, biotech corporations and start-ups, and others in the upscaling activities.

3. Materials and Methods

This study aims to document the present status of deadwood conservation in public forests from the perspective of a circular forest-based bioeconomy in Kenya and suggests policy improvements. A literature review through document content analysis was adopted in this study. Amongst other reasons, content analysis was chosen for this study because it is important for studies that seek to triangulate qualitative data to improve credibility [83]. Document content analysis is used to attain convergence of thoughts and corroboration of study findings to reduce potential bias. To achieve its aims, document content analysis uses three types of records: public records, for example, official records of an organization; personal documents, for instance, first-person accounts of actions, beliefs, experiences; physical evidence, such as fliers, posters, agenda, handbooks, and training manuals. These records are found and collected in the study setting [83,84]. This study adopted O’Leary’s process [84] for document content analysis, which consists of the following steps:

1. Gathering applicable textual data;
2. Organizing and managing the textual data;
3. Making back-ups of originals documents for footnotes and reference;
4. Assessing the genuineness of collected documents and textual data;
5. Exploring the document’s agenda and biases;
6. Exploring the contextual material and information (e.g., the purpose, tone, and style of the writing);
(7) Asking investigative questions about the textual data and collected documents (e.g., What is the type of data? Who produced it? Why was it produced, and when? What type of data was used?);

(8) Exploring and analyzing the information to generate themes.

In this study, we applied O’Leary’s [85] steps, as shown in Figure 1.

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**Table 4.** Changes in land-use in Kenya (’000 ha), 1990–2015.

| Land Use  | 1990 | 2000 | 2005 | 2010  | 2015  |
|-----------|------|------|------|-------|-------|
| Forest land | 4724 | 3557 | 4047 | 4230  | 4413  |
| Crop land  | 9258 | 9661 | 9868 | 10,072| 10,276|
| Grassland  | 41,522| 41,654| 41,496| 41,080| 40,664|
| Settlement  | 57   | 87   | 109  | 126  | 143   |
| Other lands | 1004 | 1574 | 1035 | 1044  | 1053  |
| Wetlands    | 1472 | 1504 | 1482 | 1485  | 1488  |

Total area (ha) 58,037 58,037 58,037 58,037 58,037

Source: [85].
Forests are classified into five major types. Table 5 shows the types of forest and the estimated area under each classification as of 2010.

**Table 5.** Types of forest in Kenya.

| Type of Forest       | Sub-Type                          | Estimated Area (ha) | % of Total Area |
|----------------------|-----------------------------------|---------------------|-----------------|
| Western rainforest   | Natural forest (mixed indigenous) | 144,615             | 3.5             |
| Montane forests      | Natural forest (mixed indigenous) | 1,359,860           | 32.9            |
|                      | Bamboo                            | 85,693              | 2.1             |
| Coastal forest       | Natural forest (mixed indigenous trees) | 295,871        | 7.2             |
|                      | Mangroves                         | 48,522              | 1.2             |
| Dryland forests      | Natural forest (mixed indigenous trees) | 1,875,316    | 45.4            |
|                      | Riverine forest                   | 135,231             | 3.3             |
| Forest plantations   | Public and private forests        | 186,716             | 4.5             |

Source: [86].

**4.2. The Current Use of Deadwood in Public Forests and Socio-Economic Impacts**

The forest types shown in Table 5 provide multiple benefits and diverse ecosystem services to Kenyan society. Studies show that forests contribute up to 3.6% to the GDP annually [87]. However, this contribution to GDP is a gross undervaluation considering the lack of valuation of ecosystem services, the subsistence nature of forests, and the informal marketing of most forest products [88,89]. Nevertheless, there are ongoing efforts to estimate the value of forests, including deadwood, based on their total economic value, which accounts for both use and non-use values shown in Table 6. Results from the economic evaluation of three water towers indicate that forests could contribute up to 5% of the GDP. The other key water towers in the country include Aberdares and Mt. Kenya. These water towers provide nearly 75% of the country’s water resources and are essential for Kenya’s well-being. Despite these social and economic values, most forest ecosystems are constantly threatened by degradation, biodiversity loss, and increased carbon emission from forest degradation [90,91]. In addition, there is a limitation of recent studies related to deadwood that could affect the implementation of the forest-based circular bioeconomy.

**Table 6.** The value of ecosystem services from Mau, Cherangany, and Mt. Elgon ecosystems.

| Type of Ecosystem Services | Name of Service         | Annual (KES)     | Contribution to Total Economic Value (%) |
|----------------------------|-------------------------|------------------|------------------------------------------|
| Provisioning               | Timber and Non-timber   | 22,941,590,363   | 6.33                                     |
|                            | Food Production         | 634,770,000      | 0.18                                     |
|                            | Water                   | 3,427,027,000    | 0.95                                     |
|                            | Hydropower              | 11,983,679,000   | 3.31                                     |
|                            | Biodiversity            | 5,712,786,000    | 1.58                                     |
|                            | Tourism                 | 9,300,000,000    | 2.57                                     |
| Sub-total                  |                         | 53,999,852,363   | 14.90                                    |
| Regulating                 | Water Flow              | 2,960,143,000    | 0.82                                     |
|                            | Water-Quality Regulation| 1,155,366,000    | 0.32                                     |
|                            | Carbon Sequestration     | 176,657,067,000  | 48.75                                    |
|                            | Oxygen Generation        | 118,461,049,000  | 32.69                                    |
|                            | Microclimatic Regulation| 2,099,161,000    | 0.58                                     |
| Sub-total                  |                         | 301,332,786,000  | 83.16                                    |
### Table 6. Cont.

| Type of Ecosystem Services | Name of Service       | Annual (KES)        | Contribution to Total Economic Value (%) |
|----------------------------|-----------------------|---------------------|------------------------------------------|
| Supporting                 | Soil Conservation     | 1,060,000,000       | 0.29                                     |
|                            | Nutrient Conservation | 4,499,000,000       | 1.24                                     |
|                            | Pollination           | 930,564,000         | 0.26                                     |
| Sub-total                  |                       | 6,489,564,000       | 1.79                                     |
| Cultural                   | Cultural and Spiritual| 235,358,000         | 0.06                                     |
|                            | Bequest               | 297,905,000         | 0.08                                     |
| Sub-total                  |                       | 533,263,000         | 0.15                                     |
| Grand Total                |                       | 362,355,465,363     | 100.00                                   |

Source: [86].

Nevertheless, forests provide wood and deadwood products that are traded for livelihood improvement. These products include timber from public forest plantations consumed in the construction industry in urban areas. Timber products have many sustainable development effects and also present several forest-based circular opportunities for deadwood in Kenya. For instance, in 1990, Kenya had 450 sawmills with a transformational capacity between 500 m$^3$ to 300,000 m$^3$ per year and engaging approximately 20,000 persons. As of 2015, according to Kenya Forest Service Registry, there were 32 producers of treated transmission poles, 400 producers of firewood, and 3000 individuals operating with chain saws [91,92]. Unfortunately, sawn wood production focuses on the local market. There are three broad categories of timber processors: large industries operating in public forest plantations under license, poorly equipped medium and small operators functioning in public and community forests under license, and individuals using bench saws or mobile saws operating on farm lands. The efficiency of timber processing decreases as one moves from industrial-scale processors to individual wood workers. Wood waste in industrial-scale millers is used to generate energy that is usually consumed by the wood processing firm. Due to unsustainable management conditions, the government instituted a logging ban on timber harvesting in public forest plantations [92]. However, some industrial-scale timber processors with large capacities were exempted from the logging ban and these accounted for nearly the total amount of timber on the market. In addition, the ban caused the market to be flooded with timber that had been illegally sourced from public forests. In 2018, with a focus on addressing the impacts of climate change, another logging ban was imposed, which continues to be enforced [93]. Kagombe et al. [93] studied the effects of this logging ban and concluded that the logging moratorium has both positive and negative socio-economic effects on forests and various actors. For instance, the closure of some existing sawmills reduced operating capacity leading to losses of up to KES 10 billion, increased market process of timber products, income losses up to KES 3.9 billion per year, increased operating costs for wood-dependent industries, and increased unemployment and livelihood loss. The ban on logging also affected the sustainable management of forest plantations because, during the period of the ban, meaningful planting and silvicultural operations were not undertaken. However, timber importers and private timber growers benefitted as opportunities for purchasing timber from farms skyrocketed. Other wood-based products traded in Kenya include poles, firewood, and charcoal. However, a major wood deficit was projected in 2013 [94]. Charcoal is produced in Kenya through a multi-technology application, including kilns with internal heating, kilns with external heating, and indirect heating (retorts) [95].

Wood fuel sourced from public forests is the prevalent type of energy resource in the country, contributing approximately 70% of the public energy demand [95,96]. Wood fuel is mostly used for domestic purposes, with consumption estimated at 6.5 tons per household per year [97–100]. Cottage industries, learning institutions, kiosks, and hotels constitute the second tier of users of wood fuel. On average, most cottage industries use 20–30% of...
the total operating costs on energy, which is mainly derived from firewood [100]. Moreover, the charcoal industry, which is associated with wood fuel, reportedly employs about 700,000 people, who in turn support an estimated 2.5 million household members [101]. Additionally, studies show that the charcoal sector generates KES 32 billion for the Kenyan economy [101]. Other studies have observed that charcoal has significant potential even though the revenue generated from it is low due to low tax compliance [101]. Unfortunately, formulating policy on wood fuel is challenging given the data and information uncertainty [102]. In addition, the fuelwood value chains in Kenya appear to be more developed in areas with the highest population densities. The value chain is composed of many processes with actors interacting at varying profit margins to deliver fuelwood to the consumers. Farmers are largely involved in wood production, transporters are involved in wood harvesting and transportation, and retailers are involved in wood retailing, whereas consumers have several uses for firewood [102]. The outlined wood-based value chain will have the capacity to generate more development gains if deadwood resources are holistically considered as well, even if the price of deadwood in the form of fuelwood varies across the country depending on the contextual realities of a given area. Table 7 outlines the studies conducted on fuelwood and the price in various parts of the country.

| Study            | County     | Cost of Wood in KES for Different Quantities (m³/stere/Kg/Head Lot) | Cost of 350 kg of Wood (USD) | Exchange Rate (1 USD to KES) |
|------------------|------------|---------------------------------------------------------------------|------------------------------|------------------------------|
| Ngetich et al. (2009) | Nakuru     | 500                                                                 | 0.17 m³ *                   | 22.4 ***                     | 80                           |
| Ndegwa (2010)    | Murang’a   | 800                                                                 | 1 Stere *                   | 19.4 **                      | 80                           |
| Wambua (2011)    | Kakamega   | 76                                                                  | 25 kg of head lot           | 12 **                        | 89                           |
| Boukilaid (2015) | Nyeri      | 200                                                                 | 25 kg                       | 27 ***                       | 103                          |

Note: * 1 stere = 0.65 m³ = 374 kg; 1 m³ = 575 kg (FAO 2004); ** Farm gate price, *** Retail price. Source: [101].

In the case of public forests under the jurisdiction of the Kenya Forest Service, deadwood is exploited by licensed merchants to generate revenue for the government. However, firewood from natural forests is exploited on a non-commercial basis by forest adjacent communities largely as a customary right after paying for a monthly fuelwood license (MFL). In the case of forest plantations, commercial exploitation of fuelwood is allowed considering the large amounts of wood residue left behind once a timber merchant has finished extracting their timber. According to plantation management regulations available on the Kenya Forest Service website, during log harvesting operations, the timber merchant is only allowed to cut and carry away merchantable log sections up to a diameter of 30 cm without the limbs. In addition, the merchant should cut the tree so that it leaves a stump six (6) inches in height. The merchant has 30 days to operate and vacate an allocated felling site. The remaining portions of the tree, plus the branches and the top segments of the downed tree, are later sold to large-scale fuelwood merchants using the stack method. Once the large-scale merchants have vacated a given site, forest-adjacent communities are then allowed to collect the remaining firewood as a customary right similar to the practice in natural forests. Later, after the forest station manager determines that further fetching of firewood will not be allowed, the site becomes ready for the next tree crop to be planted. Plantation establishment is done under the Plantation Establishment and Livelihood Improvement Scheme (PELIS), whereby forest adjacent communities are allocated small portions of the clear-felled forest, typically measuring up to 0.05 acres, cultivating food crops while nurturing the tree planted on their portions [102]. Frequently, the forest station manager’s decision to open an area for PELIS occurs when there is excessive wood waste on the forest floor, which may not be economical for the plot owner to carry home, but affects food crop production on those portions of land. In this case, some adjacent forest community members would illegally burn the pile of wood waste as a way of creating good crop cultivation sites [102].
Along the tree value chain, because the logs are ferried for milling, particularly by medium and small-scale timber merchants, additional deadwood is created in the log yards in the form of peeled bark and sawdust. Sometimes, due to capacity challenges accompanied by the traditional obsession with timber production alone for the construction industry, this deadwood resource is heaped in one corner of the log yard for transportation and disposal to the landfill. The yard owners set these residues on fire to create space in the log yard for more wood waste accumulation. Mbugua [103] concurs with this position and highlights that much of the timber supply deficit in the market is created by low investment in timber processing technology and a poor timber conversion ratio [104–107]. Jepng’etich [108] and UNEP [109] agree with these findings and observe the rising demand for timber and fuelwood, along with the challenge of ensuring that public forests respond to these demands in a sustainable manner. The report suggests that sustainable utilization of wood resources can be achieved through enhanced efficiency in the processing of wood. These efforts can reduce the amount of timber removed from forests, in addition to reducing emissions that are associated with climate change. Toward these strategic objectives, UNEP [109] proposes policy options, including escalating community capacity by building on sustainable charcoal production, improving firewood consumption industrial use by investing in better boilers, escalating the distribution of improved cook stoves, improving forest management, especially harvest planning, improving efficiency and applying technology, enhancing recovery rates at timber sawmills, utilizing all wood residues for the production of other bioproducts, and training sawmill operators on sustainable wood utilization. These policy options appear to be in harmony with the policy prescriptions outlined in forest and environmental conservation policy instruments in the country. However, UNEP [109] demonstrates how the alluded efficiency gains (Table 8) could be achieved by analyzing the cost estimates and emission reduction potential for forestry operations (logging), timber conversion (sawmills), charcoal production, charcoal and firewood use in cookstoves technology (households), and wood usage in industrial processes.

Table 8. Summary of cost-efficiency analysis for biomass resources in Kenya.

| Thematic Area                          | Potential Biomass Savings (m³ RWE per year) | Emission Reduction from Deforestation and Degradation (tCO₂ e per year) | Investment (USD/year) |
|---------------------------------------|------------------------------------------|-----------------------------------------------------------------------|-----------------------|
| Forest operations (harvesting)        | 10,000                                   | n/a                                                                  | 37,500                |
| Timber processing (including briquette production) | 238,000                                   | 110,838                                                              | 1,340,000             |
| Charcoal production                   | 5,658,810                                | 16,476,000                                                           | 15,642,000            |
| Fuelwood consumption at household level | 960,100                                | 2,386,000                                                            | 10,000,000            |
| Fuelwood consumption at industrial level | 1,191,000                                | 2,040,000                                                            | 11,430,000            |
| Total                                 | 8,057,910                                | 21,012,838                                                           | 38,787,000            |

Source: [109].

From Table 8, it can be observed that the efficiency measures in biomass production at all levels are viable for reducing emissions in a cost-efficient manner. However, UNEP [109] observes that even though wood is a self-regenerating resource, it becomes non-regenerative when exploitation rates exceed the ability of forest ecosystems to produce it. In addition, the lack of formal, comprehensive guidelines on sustainable management of deadwood resources (especially firewood), including sustainable disposal of solid wood wastes that are created in either forest plantation sites or natural forest sites, could affect deadwood management. Other challenges affecting the availability of deadwood resources include frequent forest fires in the dry season, non-implementation geospatial plans, low timber recovery rates, and climate change [110]. However, the major causes of forest degradation and forest cover loss are weak collaboration and coordination in forest management, the growing population, overreliance on forests for energy, the high wood deficit in the country, and the logging moratorium of 2018 affecting timber supply in the country [110].
4.3. Policy Context for Circular Bioeconomy of Deadwood

Kenya has instituted several policy actions that support the conservation of deadwood in public forests. On November 18, 2020, the government launched the Bioenergy Strategy [111] aiming to guide the use of biomass resources, including deadwood. The strategy seeks to implement the energy dimension of vision 2030 by promoting access to modern bioenergy services. Furthermore, it highlights many economic, social, and environmental benefits resulting from strategy implementation.

Previously, there was a strategy focusing on bioenergy and LPG development during the period 2015–2020. Its objectives were to enhance biomass energy resources by promoting clean energy forms, such as liquid biofuels, biogas, briquettes, and liquefied petroleum gas (LPG), for combating climate change and protecting the environment. Among its targets were shifting 50% of institutions using wood fuel to LPG, improving LPG penetration to 300,000 tons by reducing taxation, achieving 50% transition to cleaner cook stoves, ensuring that all counties collect waste and use it to generate energy and produce fertilizers, and switching 50% of all industries relying on wood fuel to more efficient energy sources, such as gasification and briquettes. The cost of implementing the strategy was estimated at KES 19.81 Billion [112].

Despite these strategic efforts, bioenergy exploitation remains a challenge on account of the attendant impacts on the environment causing climate variability and affecting rainfall patterns, health complications among bioenergy users, lack of an appropriate policy mechanism to support the production, distribution, and marketing of biomass, insufficient awareness of fast-growing tree species that can be harvested for bioenergy, inadequate data on biomass production and consumption, a disjointed approach to policy implementation among government ministries and departments responsible for biomass, inadequate recognition of biomass despite its dominance in the energy mix, use of inefficient technologies for biomass conversion to energy, and competing interests over land. In addition, doubts exist as to whether biomass plantations should be established and whether food production or commercial uses should be prioritized, along with limited awareness of the feed-in-tariff aimed at encouraging investments in renewable energy and the 10% tree cover requirement enshrined in the constitution limiting exploitation of trees as bioenergy sources [112].

The country is in the process of transitioning to using renewable energy resources, as evidenced by the development of the solar energy regulations of 2020. In addition, the revised Nationally Determined Contribution (NDC) with quite ambitious emission targets recognizes renewables in its implementation matrix [113]. As of 2017, there were several projects initiated by the government to harness the exploitation of solar power [114,115]. In a manner that appears to give credence to the great migration toward a circular bioeconomy, the government is making bold strides toward a transition to a zero-waste society. According to the Ministry of Environment and Forestry Website, the ministry has called upon the private sector to adopt the concept of a circular economy to help deal with the challenges of solid waste in the country. The website further indicates that the ministry has developed the Waste Management Policy and Bill, which incorporates a circular economy approach focusing on job creation. In support of these objectives, some private-sector actors are already leading the way to a zero-waste society. For instance, according to the Ministry of Environment and Forestry website, Sanergy, a local company, is currently recycling organic and sanitation waste to produce organic fertilizer through thermophilic composting and insect-based animal protein by rearing black soldier fly larvae, which break down the waste to form fertilizer. In 2020, Sanergy treated 12,000 tons of waste and was targeting to scale its operations capacity to process about 70,000 tons of waste per year. Another policy effort aims at promoting such bioeconomy and green economy efforts toward the circular economy by providing incentives to citizens through innovative environmental conservation award schemes. The award scheme is coordinated under the Ministry of Environment and Forestry by the National Environment Trust Fund (NETFUND) with the objectives of supporting the development of green enterprises together with development partners, such as the Swedish International Development Agency (SIDA), World Wide
Fund for Nature (WWF), United States Agency for International Development (USAID), and Japanese International Cooperation Agency (JICA) [116]. The other objectives of the award scheme include promoting the environment for green growth initiatives and enhancing public awareness of green growth initiatives [116]. Thus far, NETFUND has run four phases of the green innovation awards with expanded thematic objectives targeting environmental sustainability [117]. In 2020, achieving 10%, tree cover was one of the objectives of the award. Unfortunately, no entries sought to conserve the environment by targeting deadwood resources, which limits awareness of these resources among Kenyans. Other policy efforts of relevance to the bioeconomy of deadwood resources that have been spearheaded by the government are summarized in Table 9.

### Table 9. Key policy documents related to the management of deadwood resources.

| Document | Compatibility with the Bioeconomy of Deadwood Resources |
|----------|--------------------------------------------------------|
| Constitution of Kenya, 2010 [118] | Establishes the three organs of government which are meant to coordinate the development of policies and strategies for the bioeconomy of deadwood |
| Vision 2030 [119] | Establishes the social pillar as the foundations that drive successful deadwood bioeconomy |
| Forest Conservation and Management Act, 2016 [120] | Establishes the regulatory framework and infrastructure for sustainable management of deadwood in public forests |
| Draft Forest Policy, 2020 [121] | Provides policy direction on utilization of forest resources, including deadwood resources |
| Environmental Management and Coordination Act, 1999 [122] | It is the framework of environmental protection law that sets the parameters for innovations toward environmental sustainability in the country |
| National Biosafety Act, 2009 [123] | Concern with the risks associated with genetically modified organisms. It is relevant in guiding the biotechnology perspective of the deadwood bioeconomy |
| Science Innovation and Technology Act, 2013 [124] | Safeguards intellectual property rights related to knowledge and this promotes the bioeconomy of deadwood resources |
| Energy Efficiency and Conservation Strategy 2020 [125] | Provides incentives for energy efficiency and conservation and hence deadwood conservation |
| National Biodiversity Strategy and Action Plan whose provisions for the period 2019–2030 [126] | Establishes a framework and a road map for conservation of all types of organisms and biodiversity in public forests |
| National Solid Waste Management Strategy, 2015 [127] | Envisions a zero-waste society and provides a framework for managing municipal solid waste, but lacks provisions for the management of wood waste in public forests |
| Draft Energy Policy, 2014 [128] | Identifies bioenergy resources as critical for energy production and provides the feed-in-tariff for biomass resources which encourages the exploitation of biomass resources |

### 5. Discussion

The existential threats posed by climate change, biodiversity loss, and pollution as a consequence of unsustainable consumption of energy resources are threatening public forests and the balance between the environment, society, and economy [1,2]. However, deadwood resources sourced from public forests can simultaneously remedy the spiraling energy demands and avert the impending environmental crises, provided public forests are managed in a sustainable manner, recognizing and applying the opportunities presented in the forest-based circular bioeconomy of deadwood. In a typical circular forest-based bioeconomy, all the activities that change biomass into various product types—including materials, chemicals, food, biofuels, and animal feed—and many ecosystem services derived from healthy ecosystems are considered [12,13,50,51,75,76]. The reviewed literature
shows the underlying focus of a circular bioeconomy is to increase material and energy efficiency by exploiting the benefits of innovations that transition society toward clean production systems. Consequently, the reviewed literature has shown that many countries have shifted from traditional economic activities to a knowledge-based economy where biological resources are fully utilized for socio-economic development. Toward this goal, many countries have initiated strategies and policies for a circular bioeconomy, as shown in Table 1. For instance, the Bioeconomy Strategy for France includes promoting the photosynthesis economy, focusing on implementing COP21 agreements, and creating more value chains for existing bioproducts. Italy’s strategy also aims at redefining sustainable development by reducing dependency on fossil fuels. Portugal aims at enhancing environmental sustainability against the backdrop of global climate change, while Spain seeks sustainability, changing consumption patterns, addressing climate change, and improving competitiveness. We observe that the common underlying interest in these strategies is the quest to achieve sustainability.

Unfortunately, even with a circular forest-based bioeconomy, there are still production and consumption activities occurring in areas with public forests considered biological diversity hotspots. In our opinion, if overly ambitious energy projects consuming large amounts of biomass resources, especially deadwood, are allowed in such public forest areas, there could be an escalation of environmental threats on a global scale. Hence, policy choices must be made on how to ensure sustainability. In this context, the reviewed literature has shown that foresters and policy makers are experiencing the dilemma of how to balance the numerous interests in public forests. Lately, these choices and decisions have become more multifaceted as governments choose how best to utilize their public forests in view of competing uses and values. Public forests provide many goods and services that support many lifeforms on the planet. Reviewed studies have demonstrated that forests provide safety nets and gap fillers [23, 33], they are sources of bioactive polyphenols [25], have immense pharmacological potential [27] and sources of flavonoid and phenolic acids [30]. However, with escalating global environmental threats, attention is now shifting to the sustainable management of all components of forest ecosystems, and hence deadwood has become an interesting topic of study. As trees in the forest die, they provide deadwood resources that are important for soil carbon enhancement, enhancing the activities of nitrogen-fixing bacteria [33, 35, 36]. Deadwood also enhances forest biodiversity by improving the availability of food resources at different trophic levels and promoting the occurrence of some fungal and bird species, thereby improving ecological balance in forest ecosystems [36–49]. Interestingly, with the growing global energy demand and the increasing awareness of the value of deadwood resources, the forest management choices and decisions for foresters and policy makers mostly accustomed to consumptive forest management targeting mostly timber production alone are becoming more complicated as a critical question is posed: In the wake of the rising environmental threats, growing population and seemingly endless energy needs, are deadwood resources from public forests more important for biodiversity conservation or bioenergy production? In our opinion, using bio-based energy products from deadwood sourced from public forests for domestic (household) and industrial processes makes both environmental conservation and economic sense. However, assessing for sustainability and then harmonizing the various uses of the forest, along with a decision on whether to escalate deadwood exploitation for bioenergy, is a complex endeavor that does not have an accurate response. However, from the perspective of a forest-based bioeconomy, we observe that whether deadwood resources are important for energy production or conservation of biological diversity depends on various economic, social, and environmental effects of the present and substitutable uses of the public forest as already highlighted.

Kenya has complex development challenges that appear to be affecting the sustainable management of deadwood resources from the bioeconomy perspective. The reviewed literature shows that the rising urbanization and population growth and current over-reliance on biomass energy resources which account for nearly 68% of the country’s total
energy consumption lead to a higher risk of exacerbating the impacts of environmental crises through increased removal of deadwood from public forests. However, the country appears better placed with favorable conditions for implementing a circular forest-based bioeconomy of deadwood from public forests. Kenya has favorable climatic conditions with expansive arable land and is fairly resourced with a diverse natural resource base, as shown in Tables 4 and 5. Moreover, knowledge on the critical roles played by forest resources is increasing, as evidenced by attempts to estimate the total economic value of the three types of forest ecosystems, as shown in Table 6. The country’s rising population is also aware of the need for environmental conservation because of the concerted awareness campaigns by forest and environment stakeholders, such as the Kenya Forest Service and a host of private forest actors. Moreover, the rising population has increased the demand for wood products in the country, with the wood deficit standing at 20 million cubic meters. The reviewed literature indicates that the previously described favorable conditions are the elements and preconditions that describe a country’s competitive advantages while developing successful bioeconomy strategies and policies, as alluded to by Porter [59], BÖR [57], and BÖR [58]. Therefore, integrating the current deadwood management approach (multi-objective management) with the concept of the forest-based bioeconomy could improve the process of Kenya’s socio-economic transformation with positive environmental, social, and economic impacts on deadwood resources. However, formulating a viable policy to aggressively pursue this objective should integrate both the biotechnology and resource substitution paradigms of a forest-based circular bioeconomy, considering Kenya’s fluid social, environmental, and economic policy environment.

Kenya has a diverse forest resource, as shown in Table 5. This resource can be exploited to harness the realization of the circular forest-based bioeconomy of deadwood with both positive and negative effects. Among the key positive impacts of the current forest uses include the significant growth of forest cover and the source of deadwood between 1990–2015, as shown in Table 4, indicating the possibility of expansion of forests on private lands as the next frontier of forest development, as shown in Table 5. According to the National Strategy for Achieving 10% tree cover, as of 2019, the country’s forest cover was 7.2% [86]. Kagombe et al. [93] have estimated a forest cover of 7.4%, indicating some significant growth from 2019.

In terms of economic effects, forests contribute 3.6% to the GDP, excluding ecosystem services, non-timber forest products, and contribution to household wood energy [98]. However, recent attempts to estimate the total economic value of ecosystem services from public forests in three types of ecosystems indicated that three forest water towers alone contributed up to 5% of Kenya’s GDP, as shown in Table 6 [87]. In addition, there are many traded forest products, including timber, poles, firewood, and charcoal, whose value chains have engaged a significant number of people by providing employment and other benefits [87–90]. Wood fuel from forests contributes approximately 70% of the public energy demand, with the charcoal sector generating an annual market value of KES 32 billion [90,92]. There are many actors involved in the fuelwood value chain [101], and it demonstrates the worth of deadwood and the firewood industry in the country.

Similarly, the current public forest use has a fair share of negative impacts that might limit the achievement of the forest-based bioeconomy of deadwood resources in Kenya. According to the FAO [85], the country lost around 311,000 ha of forest due to conversion to settlements, crop farming, infrastructure development, and other uses (Table 4). Moreover, timber value addition processes are solely aimed at the domestic market. Still, there is an increasing gap between the supply and demand for wood, including deadwood, which was estimated at 13 million m$^3$ in 2013 and 20 million tons in 2020 [104,121]. The reviewed literature shows that, aside from the large-scale timber processors, most are medium and small-scale tree processors that are poorly equipped and have low timber processing and conversion efficiency [111]. Fuelwood use also contributes to health problems [111]. Additionally, there is a risk of overexploiting certain tree species because there are no guidelines for the sustainable management of deadwood resources or their derivatives,
such as the sawdust and barks generated along the tree value chain, especially following logging operations and subsequent land preparation for the growth of the next tree crop. Jung and Huxham [80] have shown that *Rhizophora mucronata* accounts for up to 10% of fuelwood extracted from Gazi Bay in Kenya’s coastal forests. This study observes that without species-specific guidelines for *Rhizophora mucronata*, its exploitation may interfere with the biological diversity of the region. Gazi Bay represents one of the conservation hotspots on the Kenyan Coast.

In this study, the review of the National Solid Waste Strategy for 2015 has shown that the document does not explicitly cover the derivatives of deadwood, such as waste wood, bark, and sawdust. Hence, at times, depending on the technological capability of these tree processors, these wood wastes are disposed of by burning or dumping bark and sawdust in landfill sites. However, with a robust waste management strategy, these wood wastes from medium and small-scale tree processors could be collected and delivered to large-scale wood processors for the production of further bioproducts and to create more value chains. Hence, the reviewed literature shows that bioenergy exploitation remains a challenge in the country due to poor policy mechanisms to support production, the inadequacy of data, and poor coordination in the implementation of biomass energy strategies [125].

However, in response, several interventions, including the development of Vision 2030, the imposition of the logging moratorium of 2018, the formulation of the waste bill and policy, environmental awards schemes, such as that held on an annual basis by National Environment Trust Fund (NETFUND), and a host of other enabling policy prescriptions outlined in Table 9 have been institutionalized. Additionally, these measures may result in the recognition and conservation of deadwood. Furthermore, from the outlined policy measures, there are institutions, systems, and infrastructure that have been established and allow the trading of forest products, including deadwood resources. This is an important precondition that favors the establishment of a forest-based bioeconomy for deadwood resources. Table 9 highlights key policy documents and how they affect the implementation of the circular forest-based bioeconomy in the country. In our opinion, the objectives of these policy documents are geared toward entrenching social equity, enhancing futurity, promoting value for the environment, and mitigating the impacts of climate change. For instance, the Forest Conservation and Management Act of 2016 establishes the institutions for community participation in forest management where deadwood is also targeted. In this “win-win” arrangement, communities living adjacent to public forests have reaped many benefits, which in turn have improved the consciousness of the need for forest protection [102]. There are also attempts to transit the economy to a zero-waste society through these policy and extra-policy measures, as evidenced by the presence of the National Solid Waste Strategy of 2015 and NETFUND’s environmental sustainability awards. These policy objectives are similar to those established by countries with robust bioeconomy strategies such as Finland, Italy, Portugal, France, and Spain, as shown in Table 1. Toward these sustainability objectives, several development partners and private entities have seized the bioeconomy opportunity. They are engaged in activities that aim to raise public awareness of the need for green initiatives. However, despite these policy interventions, there are still policy concerns about whether deadwood resources from public forests should be managed purely for biological diversity or should be exploited to address the growing energy needs in the country. In fact, these policy inadequacies appear to be affecting the sustainable management of forests in the country. According to the East African Newspaper of 2019, the logging moratorium imposed in 2018 on community and public forests appears to have worsened the environmental conservation prospects for deadwood in the country. The paper detailed that environmental crimes related to the theft of firewood (deadwood) from farms in rural areas have increased tremendously because of the cost-cutting measures instituted by some rural households following the increased demand for firewood due to a rise in fossil fuel and energy prices. These factors appear to be acting together and exert great negative pressures on the public forests and
the environment, especially the management of deadwood. Kagombe et al. [93] has also warned about these impending existential forest and environmental threats in Kenya. However, regarding the question of whether deadwood should be conserved for biological diversity or be increasingly exploited for energy in Kenya’s public forests, we observe that the above negative impacts of biomass consumption accompanying current public forest use may significantly be diminished and even show better environmental and economic returns if forest resource use efficiency gains are harnessed through circular bioeconomy processes that holistically capture energy products and other bioproducts from the deadwood. Deadwood itself is a regenerative raw material for producing energy if it is sustainably sourced and replaced through a cycle of re-growths over time. Due to the biological cycle of deadwood, its use in energy production can offset the emission from other more polluting fuel sources such as kerosene. In theory, studies show that when carbon is absorbed by trees, it is released into the atmosphere as carbon dioxide and other gases. Therefore, using biomass such as deadwood from public forests provides energy and conserves biological diversity. However, the forest takes considerable time to reach its original size before it is cut in the carbon recapture process following logging and fuelwood collection operations. Accordingly, bioenergy resources such as deadwood will continue to play a crucial role as an environmentally and economically friendly substitute for fossil fuels and provide much-needed energy security for the country. However, the replacement of fossils fuels will not happen overnight. Globally, following the recent financial problems faced by the forest sector, there have been calls for more forest biomass production for a range of bio-based energy products [64–66]. Forest biomass such as deadwood appears to support energy production because of its competitive advantages over other fuel sources such as fossil fuels. It can be processed to produce many energy bioproducts [71–77]. In the case of Finland, the Climate News Network [75] concurs with these studies and suggests the biotechnological application involving fluidized gasification and biorefineries of wood and deadwood. If Kenya transitions to a circular forest-based bioeconomy where deadwood resources are holistically exploited, the new value chains created may stimulate increased interest in higher value bioproducts, such as biochemicals and biomaterials, providing energy and replacing similar fossil-based products. In addition, there will be opportunities for increasing energy generation by technologies that capture energy from forest residues, including deadwood. The reviewed literature has also shown that there are recurrent fires in public forests during the drier seasons of the year. Even though these fires affect forests negatively, the deadwood left behind represents another opportunity for new deadwood value chains from a forest-based bioeconomy perspective. In terms of supporting wood salvaging, we observe that when deadwood is left on the forest floor, it will naturally decompose, releasing emissions into the atmosphere. Therefore, it is better to recover this deadwood and change it to bioenergy to secure lower net emissions from bioenergy in the long run. In addition, while evaluating Kenya’s current forest management practice, more deadwood value chains can be created by discouraging the practice of burning wood residues in forest plantation sites as a waste disposal method because carbon is immediately released without the recovery of the energy needed to offset fossils. Several studies appear to agree with these deadwood policy suggestions and emphasize the need for robust mechanisms that would enhance efficiency in wood utilization. UNEP [89], KFS [92], and Kagombe et al. [93] agree with the policy options for forest biomass conservation. UNEP [89] has even demonstrated a cost-efficiency analysis of deadwood resources, such as charcoal and firewood, as shown in Table 8. However, to meet Kenya’s NDC obligations related to cutting emissions in the energy sector, there is an urgent need to leverage the abundant solar irradiation opportunities and pursue aggressive energy resource substitution prescriptions that increase the efficiency of the utilization of available biomass and slowly replace fossil-based fuels with increased electrification through other forms of renewable energy, such as hydro-power, geothermal, wind, and solar power resources, which appear to be vast in the country. The East African Newspaper in 2019 supports this policy option by expressing that the country needs a com-
plete energy shift from using biomass such as firewood to electrification from renewable energy sources, such as hydro, wind, and solar energy sources. Kenya is already a leader in renewable energy on the African continent, with over 60% of its power coming from the previously mentioned renewable sources. There are signs of the country’s advances in exploiting the abovementioned energy sources, considering the investments and solar energy regulations that are still under development. This way, deadwood from public forests will be purely managed in a sustainable way for non-consumptive uses and provision of ecosystem services, which are currently underestimated in national economic data on the contribution of forestry to socio-economic growth. Furthermore, this study urges the government to escalate the incentives for improving efficiency in wood conversion to sustainably manage deadwood resources in public forests.

In summary, from the perspective of a forest-based bioeconomy, there are many opportunities for biomass flow in the value web for deadwood resources sourced from Kenya’s public forests, which can be summarized as shown in Figure 2. Deadwood can be further processed into directly produce charcoal, pellets, briquettes, electricity, or chips. However, when advanced biotechnology associated with the circular bioeconomy is applied, there is the potential for developing new bioeconomy products, such as colorants, organic acids, amino acids, and enzymes, as shown in Figure 2. These new products have the potential of transforming society to a zero-waste state and creating new product value chains with greater positive social, economic, and environmental impacts on the management of public forests.

![Figure 2. Opportunities for biomass flow in value web-based on deadwood from public forests in Kenya.](image)

6. Conclusions

This study explored whether deadwood resources from public forests in Kenya should be exploited for bioenergy production or left to decompose for biological conservation. The study also provided suggestions on how public forest policy could be improved in the context of a circular forest-based bioeconomy. The reviewed literature demonstrates that, if sustainably managed, deadwood resources from public forests have the potential to support the balance between society, economy, and the environment by inducing new development effects. Hence, many countries with rapidly developing bioeconomy policies and strategies are focusing on deadwood conservation. Despite the definitional variations, the reviewed literature has demonstrated that a forest-based circular bioeconomy of deadwood is likely to be a major guiding paradigm in forest management that will accelerate the transition from fossil-based raw materials, products, and services through its ability to create deadwood bioeconomy linkages to the whole forest value chain. Such linkages are likely to increase
interest in forest resources by increasing economic activities. Kenya is also desirous of these forest-based bioeconomy gains based on deadwood resources. Despite the complex development context, there is a desire to embrace a forest-based circular bioeconomy of deadwood through policy formulation. Even though not directly related to deadwood, the country recently enacted a more robust Forest Conservation Management Act 2016 with an ambitious National Determined Contribution for reducing carbon emission. There are also attempts to develop regulations for the sustainable utilization of renewable energy sources such as solar power besides providing incentives for sustainable environmental protection through awards schemes. The implementation of these policy improvements can help to extract maximum value from deadwood resources. However, in the current socio-economic context, a robust forest-based circular bioeconomy centered on deadwood resources will be achieved by improving wood and deadwood conversion efficiency, using biotechnological applications where new deadwood bioproducts are produced, and substituting resources by exploring the vast solar power resources as a replacement for the highly polluting fossil-based fuels. Pursuing these policy approaches will reduce the accumulation of wood wastes and promote the sustainable conservation of biological diversity because less deadwood is extracted from public forests for energy production. However, in the meantime, sustainable guidelines for the sustainable conservation and management of deadwood should be urgently developed. Moreover, with the current scenario where deadwood removal is legally sanctioned, there is the need to improve sustainability by minimizing the negative impacts of extracting large volumes of deadwood from forest ecosystems. Further location-specific studies are required to weigh the impacts of large-scale deadwood removal against the chances of the economics of scope activities when bioeconomy actors aim to optimize value-added and sustainable use of forest resources. In addition, strengthening stakeholders in deploying innovation approaches for orienting economies of scope rather than economies of scale may require major leverage to extract higher added value from lower volumes of deadwood resources, leaving a greater amount for the natural protection of the remaining forest reservoirs.

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