

Evaluation of waste agricultural residue for sustainable Africa biofuel production: SWOT and SMART outlooks

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ABSTRACT

This review examines the current status of waste agricultural residue (WAR) resources for biofuel production within the African context. Africa's energy demand is still largely met by fossil fuels, which are rapidly depleting. This depletion, coupled with rising energy consumption across the continent, poses a significant threat to future energy security. Furthermore, the extensive reliance on fossil fuels has resulted in serious environmental challenges, highlighting the urgent need for sustainable alternative energy sources such as biofuels. Waste agricultural residues have widely been identified as abundant, sustainable and promising feedstocks for biofuel production. However, the large-scale implementation of WAR-based biofuel systems across Africa remains constrained by a limited understanding of their strengths, weaknesses, opportunities and threats (SWOT). To address this gap, this review presents a comprehensive SWOT analysis alongside a specific, measurable, achievable, relevant and time-bound (SMART) roadmap to guide the development of viable continental WAR-based biofuel production. In addition, the review assesses WAR resources across Africa's major economies and evaluates key conversion pathways, including bioethanol, biogas, biomethane and biohydrogen production. Finally, it discusses the feasibility of sustainable WAR-based biofuel production in Africa and demonstrates its potential contribution to achieving the United Nations Sustainable Development Goals (SDGs).

1. Introduction

The African continent faces persistent challenges related to energy supply, growing energy demand, and environmental sustainability. These challenges underscore the need to diversify the energy mix by promoting cleaner and renewable energy sources, including biofuels produced from waste agricultural residues (WAR). Large quantities of WAR are generated annually through extensive agricultural production and agro-industrial processing activities [1,2]. As a renewable feedstock, WAR offers considerable potential for the production of

environmentally friendly biofuels and other biobased products. However, maximizing its valorisation requires a comprehensive understanding of its strengths, weaknesses, opportunities and threats (SWOT), alongside the application of a specific, measurable, achievable, relevant and time-bound (SMART) framework to guide implementation. Successful WAR valorisation could simultaneously address energy insecurity, environmental degradation and economic challenges associated with continued reliance on fossil fuels.

Biofuels derived from WAR have emerged as a promising alternative to conventional fossil fuels. Although many African countries remain

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developing economies, rapid economic growth and urbanisation in countries such as Nigeria, South Africa, Egypt, Morocco, Rwanda, Ghana and Kenya are driving substantial increases in energy demand. This growing demand presents a strategic opportunity for governments and private investors to accelerate the deployment of WAR-based biofuel technologies for both energy generation and transportation. Consequently, evaluating the technical, economic and strategic feasibility of large-scale biofuel production from WAR has become increasingly important.

Africa produces enormous quantities of agricultural residues from major crops, including maize, rice, banana, potato, sugarcane, cassava, yam, sorghum and millet. During the 2023/2024 production season, the continent harvested nearly 91 million metric tonnes of maize, with Nigeria and South Africa accounting for the largest shares. Rice production reached approximately 33.6 million metric tonnes, led by Nigeria, Egypt, Madagascar, Tanzania, Mali, Guinea, Côte d'Ivoire, Sierra Leone, Senegal and Ghana. Similarly, Africa produces more than 17.5 million metric tonnes of bananas annually, with Angola, Tanzania, Rwanda, Kenya, Egypt, Burundi, Cameroon, Sudan and Ethiopia serving as the principal producers. Potato production exceeds 22 million metric tonnes per year, with Egypt, Algeria, South Africa, Kenya, Morocco, Malawi, Nigeria, Ethiopia, Tanzania and Rwanda ranking among the leading producers. Details of crop production capacities across major African countries are presented in Table 1.

The high production volumes of these crops generate substantial quantities of agricultural residues that remain largely underutilised [13]. Although comprehensive continental estimates of annual WAR generation are limited, the available data for major crops indicate a considerable and sustainable biomass resource (Table 1). Several studies have highlighted the abundance, availability and bioenergy potential of WAR across Africa, demonstrating its suitability as a feedstock for biofuel production [14]. Nevertheless, existing studies have largely focused on resource availability and conversion technologies, while providing limited guidance on strategic implementation pathways. In particular, there is a notable lack of comprehensive frameworks that integrate SWOT and SMART analyses to support the successful commercialization of WAR-based biofuel systems.

Addressing this knowledge gap is essential because the large-scale deployment of WAR-based biofuel industries requires not only

abundant feedstock but also strategic planning, supportive policies, technological readiness and stakeholder coordination. Accordingly, this review evaluates the feasibility of biofuel production from WAR across Africa by integrating continent-wide SWOT and SMART analyses with country-specific evidence, while aligning the discussion with the relevant Sustainable Development Goals (SDGs). Such an integrated assessment provides a strategic perspective for advancing sustainable biofuel development on the continent.

The widespread cultivation of agricultural crops across Africa will ensure a continuous supply of residues that could sustain year-round biofuel production. However, several constraints remain, including the need for extensive biomass pretreatment, the perishability of fresh residues, limited technological capacity, inadequate infrastructure, and significant capital investment requirements. Despite these challenges, the opportunities associated with WAR valorisation are substantial. Expanding biofuel production could stimulate rural industrialisation, create employment opportunities, generate additional income for farming communities, improve waste management, enhance energy security, and reduce greenhouse gas emissions through the substitution of fossil fuels with renewable alternatives. Overall, WAR-based biofuel production represents a promising pathway towards a circular bioeconomy and sustainable energy transition in Africa. A comprehensive evaluation of its technical, economic and strategic potential is therefore essential to determine its long-term viability. This review provides an analytical assessment of the SWOT and SMART frameworks of WAR-based biofuel production across Africa, offering evidence-based insights for policymakers, investors, researchers and other stakeholders. The findings are expected to support informed decision-making, facilitate the development of WAR-based biorefineries, and contribute to the transition towards sustainable, low-carbon energy systems across the continent.

2. WAR resource assessment in africa

Agricultural activities such as crop production and agro-processing across Africa generate substantial quantities of waste agricultural residue. The literature consistently identifies these residues as one of the continent's most abundant yet underutilised biomass resources. While estimates vary due to differences in assessment methodologies and study focus, studies collectively demonstrate that Africa possesses significant agricultural residue resources capable of supporting renewable energy production and broader bio-based industries. Several studies have attempted to estimate the magnitude of WAR generation across Africa, although the reported values differ considerably depending on the scope of assessment. Furthermore, persistent challenges in accurately quantifying these resources and translating their potential into practical applications have been identified. Obi et al. [15] estimate that Africa generates over 998 million tonnes of agricultural residues annually, while Kamdem et al. [16], in their continent-wide assessment covering 54 countries, 34 crops and 59 residue types (2011–2021), provide a comprehensive estimate of WAR biomass availability. Using Food and Agriculture Organization (FAO) data, the latter study estimated an average of approximately 1.01 billion tons of dry crop residues available annually. Of this total, 0.53 billion tons are surplus primary residues and 0.16 billion tons are surplus secondary residues that could be used sustainably for bioenergy. Also, Same et al. [17], using a more comprehensive inventory of 85 residue types, estimated approximately 102.3 gigatonnes of fresh residues (equivalent to about 62.1 gigatonnes of dry residue biomass). Although these estimates are not directly comparable because of methodological differences and reporting units, both studies consistently indicate that agricultural crop residues constitute an enormous and largely untapped biomass resource. The dominant agricultural crop contributors include maize, sorghum, cassava, millet, rice, sugarcane and cocoa, reflecting the importance of staple crop production across the continent.

Furthermore, the availability of WAR is closely associated with

Table 1
Major economies in Africa with WAR potential for biofuel production.

Country	Economy size (USD)	Major crops	Data year	Estimated WAR (Million Mts)
South Africa	410.34 billion	Maize, sugarcane, potatoes	2017	13.5 [3]
Egypt	347.34 billion	Wheat, sugarcane, sugar beet	2019	35 [4]
Algeria	268.89 billion	Potatoes, wheat, barley, watermelons	2017	7 [5]
Nigeria	188.27 billion	Cassava, yam, maize, rice, sorghum	2024	> 84 [6]
Morocco	165.84 billion	Wheat, barley, sugarcane, potatoes	2013	> 19 [7]
Kenya	131.67 billion	Sugarcane, maize, tea, coffee	2022	5–24 [8]
Ethiopia	117.46 billion	Maize, teff, sorghum, wheat, tea	2021	88 [9]
Angola	113.34 billion	Cassava, sugarcane, maize, rice, bananas	2020	5 [10]
Cote d'Ivoire	94.48 billion	Cocoa, yam, cassava, cashew nuts, rice	2019	17 [11]
Ghana	88.33 billion	Cassava, yam, plantains	2020	39 [12]

Note: The size of a country's economy is its gross domestic product (GDP), and GDP is the sum of monetary value of all finished goods and services produced within a country during a financial year (in this case financial year 2025). The estimated WAR in million metric tonnes (million Mts) and the data year in the current study are based on reported data.

agricultural productivity. Countries with extensive cereal, tuber and sugar crop production—including Nigeria, Ethiopia, Egypt, South Africa and Ghana—account for a significant proportion of Africa's biomass resources. Regarding the regional WAR contribution, Röder et al. [18] estimated that Sub-Saharan Africa alone generates approximately 147 million metric tonnes of primary and processing residues annually, highlighting the concentration of residue generation within regions characterised by intensive agricultural production. Collectively, these findings suggest that biomass availability is geographically uneven and largely determined by crop distribution patterns. Similarly, Same et al. [19] estimated that West Africa could annually generate about 402 million metric tons (Mt) of WAR biomass, mainly from cassava, maize, rice and sorghum residues. Cassava contributes the largest share (35%) of the biomass energy potential, while Nigeria and Ghana have the highest energy potential. Agricultural residues could supply approximately 20.13% of the region's 2022 energy demand (3.05 EJ), highlighting their potential in strengthening regional energy security. Also, Akinbile et al. [20] reported that agricultural residues in East Africa are derived mainly from maize, coffee, tea, sugarcane and horticultural crops. Kenya, Ethiopia, Tanzania and Uganda generate substantial volumes of sugarcane bagasse, maize stover and coffee husks, with Kenya and Ethiopia alone contributing more than 110 million metric tonnes of residues annually. This could provide concentrated feedstock streams that are well suited for on-site energy generation and lignocellulosic biofuel production. However, the region's longstanding practice of using agricultural residues as livestock feed and soil mulch highlights an important sustainability trade-off. Excessive diversion of these residues to biofuel production could compete with existing agricultural functions, emphasizing the need for integrated resource management and comprehensive sustainability assessments to balance energy production with soil health and livestock requirements. Moreover, Akinbile and co-workers [20] reported that agricultural residue generation in Southern Africa is closely associated with the region's large-scale farming systems, particularly in South Africa, Zambia, Zimbabwe and Malawi. South Africa produces approximately 13.5 million metric tons (Mt) of residues, followed by Zambia (11.2 Mt), Zimbabwe (7.8 Mt) and Malawi (approximately 2.9 Mt). These residues are derived predominantly from maize stover, wheat straw, sugarcane residues, cassava peels, soybean straw and fruit-processing wastes, highlighting the region's considerable feedstock base for biofuel production. Despite this abundance, widespread residue burning, especially in Zambia and Zimbabwe, continues to limit resource utilization while contributing to environmental pollution. In the same vein, North Africa possesses significant agricultural residue resources, generating an estimated 80 million metric tons annually, primarily from Egypt, Morocco, Tunisia and Algeria. Residues originate mainly from cereal cultivation, olive production and sugar-beet processing, producing large quantities of wheat straw, rice straw, olive-mill waste and sugar-beet pulp. Among these, Egypt's rice straw represents one of the region's most underutilised biomass resources. Its conversion into bioethanol, biogas or other bio-based products would not only reduce environmental impacts but also enhance renewable energy production and support the transition towards a circular bioeconomy. Overall, the evidence suggests that both Southern and North Africa possess substantial biomass resources, with the principal challenge lying in shifting from feedstock to the development of effective collection, utilization and policy frameworks capable of transforming agricultural residues into sustainable bioenergy resources.

Country-specific studies reinforce continental WAR assessments while providing insight into the diverse utilization opportunities for agricultural residues. In Ethiopia, Tolessa [9] estimated approximately 88 million metric tonnes of crop residues from 44 residue categories generated by 30 crop types during the 2020/2021 production year. In Cameroon, agricultural residues contribute approximately 96% of the country's bioenergy potential, demonstrating the strategic importance of biomass within national renewable energy portfolios [21]. Likewise,

studies from Morocco emphasize the suitability of agricultural residues for compost production, soil fertility enhancement and biofuel generation [7]. In Benin, Akpahou et al. [22] reported that agricultural residues account for 98% of the country's biofuel feedstock potential, with maize, cotton and cassava contributing the largest shares. Similarly, Nigeria generates more than 84 million metric tons of agricultural residues annually, mainly from cassava, yam, maize, rice and sorghum production. These national studies consistently demonstrate that agricultural residues have considerable potential for supporting renewable energy, soil management and circular bioeconomy initiatives.

Despite broad agreement regarding the abundance of WAR, the literature consistently identifies underutilisation as a major limitation. In many African countries, agricultural residues continue to be burned openly, left to decompose, or discarded after harvest, resulting in greenhouse gas emissions, air pollution, nutrient depletion and loss of potentially valuable biomass resources [17,21]. This disconnect between resource availability, and resource utilization suggests that technical potential has not been adequately translated into economic or environmental benefits due to infrastructural, technological and policy constraints. A notable limitation across the reviewed literature is the absence of coordinated residue inventories. Most studies estimate residue availability on a crop-specific basis or evaluate biomass according to particular feedstock categories, rather than presenting comprehensive national or continental assessments. Consequently, the reported estimates vary considerably, making direct comparisons difficult and limiting the development of consistent resource-planning frameworks. As noted by Tolessa [9], Same et al. [19] and Awaifo et al. [23], methodological inconsistencies and limited data availability remain major obstacles to accurately assessing Africa's agricultural residue resources. Overall, present evidence shows that Africa possesses abundant agricultural residues capable of supporting sustainable biofuel production and circular bioeconomy development. Nevertheless, existing research is characterised by fragmented datasets, inconsistent estimation approaches and limited continent-wide inventories. Future research should therefore prioritize standardised residue assessment methodologies and comprehensive biomass databases to improve resource quantification, facilitate regional comparisons and support evidence-based policy development for sustainable agricultural residue management.

In comparison to the African continent, Asia produces billions of tonnes of waste agricultural residues annually, making it one of the world's largest biomass resource bases. Crop residues such as rice straw, wheat straw, sugarcane bagasse, cassava waste and oil palm biomass dominate the source of WAR. China alone generates more than 870 million tonnes of crop straw annually, while India produces approximately 680 to 869 million tonnes of crop residues. In Southeast Asia, more than 590 million tonnes of agricultural residues, including crop stubbles, straw and husks, are produced each year. This abundant biomass provides significant opportunities for renewable energy production, improved waste management and reduced dependence on fossil fuels. The valorisation of agricultural residues across Asia reflects country-specific resources and utilization pathways. In India, approximately 500 to 550 million tonnes of crop residues (predominantly rice and wheat straw) are converted into WAR-based bioethanol and compressed biogas under the National Policy on Biofuels. These initiatives simultaneously promote renewable energy production and address the environmental challenge of open-field stubble burning [24]. Also, Thailand has prioritized decentralised biorefineries that process sugarcane bagasse, cassava residues and rice straw into WAR-based bioethanol using enzymatic hydrolysis and thermal pretreatment technologies [25]. In Indonesia and Malaysia, the world's leading palm oil producers, oil palm residues—including empty fruit bunches, palm kernel shells and palm oil mill effluent—are increasingly converted into renewable electricity, biomethane and biodiesel, thereby improving resource efficiency within the palm oil industry [26]. Meanwhile, China leads the region in agricultural bioenergy research, utilizing corn stover

and cereal straw for biogas, biochar and other bio-based products through anaerobic digestion, pyrolysis and gasification technologies [27]. Collectively, these examples demonstrate that Asia has advanced beyond simple residue disposal to integrated biomass valorisation systems that combine biochemical processes with thermochemical technologies to maximize energy recovery from WAR and support low-carbon development.

Moreover, Latin America and the Caribbean (LAC) possess one of the world's richest agricultural biomass resources, generating over 590 million tonnes of waste agricultural residues annually. These residues, which include crop stubbles, straw, husks and agro-industrial by-products, represent a substantial yet historically underutilised resource for renewable energy and bio-based industries. Government surveys and scientific assessments have consistently highlighted the significant availability of both direct and indirect biomass resources across the region. Agricultural residue generation is highly concentrated in major Latin American agricultural economies, particularly Brazil and Colombia, which together account for approximately 97% of Latin America's agricultural waste biomass. Their extensive cultivation of sugarcane, maize, wheat and bananas generates large quantities of sugarcane bagasse, maize stover and cobs, wheat straw and banana residues, providing a strong feedstock base for biofuel production [28]. Mexico also represents a major biomass producer, generating approximately 74.85 million tonnes of maize residues and 12.31 million tonnes of banana residues annually [29]. These resources have an estimated potential to produce 9.68 million tonnes of bioethanol and 6.63 billion m³ of biomethane, equivalent to approximately 137 756 GWh of energy and representing about 5.6% of Mexico's total national energy supply [29]. Consequently, agricultural residues across the LAC region are increasingly being valorised into bioethanol, biomethane, sustainable aviation fuel (SAF) and other bio-based chemicals, supporting circular economy strategies, reducing environmental pollution, and strengthening regional energy security. The region demonstrates considerable potential to transform abundant agricultural wastes into high-value bioenergy products through improved biomass management, technological innovation and supportive policy frameworks.

3. Conversion pathways (bioethanol, biogas, biomethane, biohydrogen)

Biofuel production from waste agricultural residues (WAR) in Africa is predominantly based on second-generation conversion technologies that utilise lignocellulosic biomass instead of food-based feedstocks [30]. The principal conversion pathways include bioethanol, biogas, biomethane and biohydrogen, each differing in technological maturity, infrastructure requirements, commercial readiness and potential contribution to Africa's renewable energy transition. Although the continent has abundant agricultural residues capable of supporting these technologies, their successful deployment depends on overcoming persistent technical, economic, institutional and policy constraints.

Bioethanol production from WAR relies on the pretreatment and hydrolysis of lignocellulosic biomass to release fermentable sugars, which are subsequently converted into ethanol through microbial fermentation [31]. Feedstocks such as maize stover, rice straw, wheat straw and sugarcane bagasse are particularly suitable because of their high cellulose and hemicellulose contents. Unlike first-generation bioethanol, second-generation production avoids competition with food crops while simultaneously addressing agricultural waste disposal challenges [32]. Countries with extensive cereal and sugarcane production, including Nigeria, South Africa and Ethiopia, generate sufficient residues to support both decentralised and industrial-scale bioethanol production [9]. Nevertheless, commercial expansion remains constrained by the high costs of biomass pretreatment, limited availability of hydrolytic enzymes, and inefficient residue collection, transportation and storage systems [17]. These limitations indicate that advances in pretreatment technologies, enzyme development and

integrated biomass supply chains are essential for improving the economic competitiveness of lignocellulosic bioethanol.

Among the available WAR conversion technologies, anaerobic digestion (AD) for biogas production is the most technologically mature and widely implemented across Africa (with South Africa leading in this regard), particularly within rural and peri-urban communities [33,34]. Anaerobic digestions systems typically co-digest crop residues, including maize stalks, banana residues and vegetable wastes, with animal manure to enhance microbial activity and methane production [35]. This integrated approach aligns well with Africa's predominantly mixed crop-livestock farming systems while providing renewable energy for cooking, lighting and small-scale electricity generation. An additional advantage is the production of nutrient-rich digestate, which can be recycled as organic fertiliser, thereby promoting circular nutrient management and improving soil fertility [36]. Despite these benefits, widespread adoption remains limited by seasonal feedstock availability, inadequate technical capacity, insufficient financing mechanisms, weak institutional support and low public awareness [37–39]. These barriers suggest that technological maturity alone is insufficient to ensure large-scale dissemination without complementary policy and capacity-building initiatives.

South Africa illustrates both the opportunities and challenges associated with biogas development [14]. Of approximately 700 biogas plants installed by 2017, fewer than half remain operational, largely because of inadequate technical expertise in operational management. Most operational systems primarily supply cooking and heating applications, while commercial upgrading to biomethane remains rare, with the Athlone facility in Cape Town representing one of the few large-scale examples. Nevertheless, decentralised biodigesters installed at households, on farms, at institutions and in agro-industries demonstrate the technology's potential to improve rural energy access, enhance waste management, generate organic fertiliser and create employment opportunities [14]. Integrating upgraded biomethane into existing gas infrastructure could reduce transition costs while accelerating market development.

Biomethane, produced through the purification and upgrading of biogas, contains a substantially higher methane concentration, enabling its use for natural gas substitution, industrial energy applications, grid injection and transportation fuels [36], [40], [41]. Compared with conventional biogas, biomethane offers higher energy density and greater market flexibility. Although commercial deployment remains limited across Africa, the technology has considerable potential in agro-industrial regions characterised by concentrated residue generation, including sugar-processing industries, livestock operations and agro-processing estates [42–44]. However, widespread adoption is constrained by high upgrading costs, limited access to purification technologies, underdeveloped gas infrastructure, and the absence of supportive regulatory and market frameworks [45]. Consequently, realising the potential of biomethane will require coordinated investments in upgrading technologies, gas infrastructure, and enabling policies.

Biohydrogen represents the least mature but arguably the most innovative WAR conversion pathway [46,47]. Biological production processes, particularly dark fermentation and photo-fermentation, convert pretreated lignocellulosic biomass into hydrogen under anaerobic conditions [48–50]. Hydrogen combustion produces only water, therefore biohydrogen is widely recognised as a promising carbon-free fuel capable of supporting long-term decarbonisation strategies [51]. Dark fermentation is especially attractive for decentralised applications owing to its relatively mild operating conditions and compatibility with existing organic waste management systems [47]. Moreover, integrating dark fermentation with anaerobic digestion allows residual biomass to be converted into biogas or biomethane, thereby improving overall energy recovery within integrated biorefinery systems [52].

Despite its considerable long-term potential, biohydrogen production in Africa remains largely confined to laboratory research and pilot-

scale demonstrations [53]. Commercialization is hindered by low hydrogen yields, expensive pretreatment requirements, limited optimisation of hydrogen-producing microorganisms, inadequate technical expertise, and the absence of dedicated hydrogen infrastructure and policy support [47], [50], [54], [55]. Consequently, substantial investments in research, innovation, demonstration projects and human capacity development are required before biohydrogen can become a significant component of Africa's renewable energy portfolio.

The four major WAR-based biofuel pathways occupy different positions along the technological development spectrum. Biogas remains the most commercially established technology because of its compatibility with smallholder farming systems and its proven environmental and socioeconomic benefits. Bioethanol provides substantial opportunities for large-scale valorisation of abundant lignocellulosic residues but requires improvements in pretreatment efficiency and biomass logistics to become economically competitive. Biomethane offers a higher-value gaseous fuel with broad industrial applications, although its expansion depends on investments in upgrading technologies, gas infrastructure and supportive regulatory frameworks. In contrast, biohydrogen represents a strategic long-term option with considerable decarbonisation potential but remains constrained by technological immaturity and limited commercial readiness. Collectively, these pathways demonstrate that Africa's bioenergy transition will depend not on a single technology but on an integrated portfolio of conversion pathways tailored to regional feedstock availability, technological capabilities, infrastructure and policy priorities. Such a diversified approach would maximize resource utilization, strengthen circular bioeconomy principles, and enhance the contribution of agricultural residues to sustainable energy development ([47], [56]).

4. Trade-offs of agricultural residue use for soil amendment versus biofuel

The utilization of agricultural residues for biofuel production presents a significant sustainability challenge because the same biomass resource can be employed for agricultural soil nutrient-enrichment functions. The current literature consistently identifies potential trade-offs between retaining residues on agricultural land to maintain soil quality and diverting them to biofuel production to support renewable energy transitions [17,57–61]. Rather than representing competing objectives, these functions are inherently interconnected, requiring management strategies that balance agricultural productivity with biofuel production development.

Waste agricultural residues contribute substantially to nutrient cycling, soil organic carbon accumulation, erosion control, moisture conservation and improvements in soil biological activity. Chen and Liu [58] demonstrate that residue incorporation enhances soil microbial communities, increases water-holding capacity and improves overall soil fertility, thereby sustaining long-term agricultural productivity. These findings suggest that residues provide ecosystem services that extend beyond nutrient replacement and amendment, reinforcing soil resilience under changing climatic conditions. Consequently, indiscriminate residue removal for biofuel feedstock may compromise soil functions that are essential for sustainable crop production.

In contrast, numerous studies highlight the considerable socioeconomic and environmental benefits associated with utilizing agricultural residues for biofuel production [14]. Residues represent an abundant lignocellulosic feedstock capable of producing low-carbon fuels that reduce dependence on fossil energy while contributing to greenhouse gas (GHGs) mitigation. Beyond climate benefits, WAR-based biofuel offers opportunities for rural employment, additional farm income, and regional economic development through the establishment of biomass processing industries [57,59,60]. From this perspective, agricultural residues are increasingly viewed as strategic resources within the circular bioeconomy rather than agricultural waste requiring disposal. Thus, it is necessary to caution against maximizing WAR

extraction without considering ecological thresholds. Excessive residue removal accelerates nutrient depletion, reduces soil organic matter, and might increase dependence on synthetic fertilizers to maintain crop yields. Such reliance not only increases production costs but may also offset some of the environmental gains associated with biofuel production through higher GHGs emissions linked to inorganic fertilizer manufacture and application. These observations illustrate that optimizing biofuel production without accounting for ecosystem functions can generate unintended environmental and economic consequences.

To illustrate this potential trade-off, Same et al. [17] estimated that approximately 102.256 Gt of freshly generated WAR are produced across the continent annually, corresponding to about 62.117 Gt of dry WAR biomass, with a theoretical bioenergy potential of approximately 207.127 EJ. While these figures demonstrate Africa's substantial biofuel potential, the authors argue that large-scale residue harvesting could adversely affect soil quality, freshwater ecosystems and competing agricultural uses. Importantly, since residues already support livestock feeding and soil nutrient replenishment in many rural farming systems, biofuel development must take into account existing livelihood dependencies. Hence, sustainable WAR management should prioritize balanced allocation rather than complete retention or extensive removal. Several authors recommend that only approximately 20% to 50% of available agricultural residues should be harvested for biofuel production, while the remainder should be retained to preserve soil health and maintain ecosystem functions [58–61]. Although the exact proportion varies according to crop type, climatic conditions, soil characteristics and management practices, this threshold-based approach reflects increasing recognition that residue management should be site-specific rather than a generalized prescription.

The sustainability of WAR-based biofuel systems depends less on the quantity of WAR available than on how residues are allocated among competing uses. Future biofuel strategies should therefore integrate agronomic, ecological and socio-economic considerations to identify WAR-harvesting thresholds that maximize renewable energy production without compromising long-term soil fertility, agricultural productivity and rural livelihoods. Such integrated management frameworks are essential for achieving the objectives of both sustainable agriculture and circular bioeconomy.

5. SWOT analysis

5.1. Strength of biofuel production from WAR in Africa

The use of waste agricultural residues (WAR) in the production of biofuels has several strengths connected to resource availability, environmental sustainability and the socioeconomic development of rural populations (Fig. 1). Agricultural residue has been identified as a strategic and sustainable feedstock for biofuel production in Africa due to its abundance, renewable nature and alignment with circular bioeconomy principles. Studies have shown that the high lignocellulosic composition of residues such as maize stover, cassava peels, sorghum and millet straw, rice husks and sugarcane bagasse are a major strength. These materials contain substantial proportions of cellulose and hemicellulose (typically ranging from approximately 30% to 50% and 20% to 35% respectively), while some residues also possess considerable starch content, making them suitable substrates for the production of bioethanol, biogas and other advanced biofuels [3,62–66]. These studies demonstrate that the biochemical composition of these agricultural residues provides a strong technical foundation for biofuel production without competing directly with food crops. This distinguishes second-generation biofuels from first-generation biofuels and reinforces their sustainability credentials.

Another major desirability of WAR for biofuel production is its extensive availability across the African continent. Although global agricultural waste production exceeds one billion tonnes annually, African countries contribute significantly through increasing crop

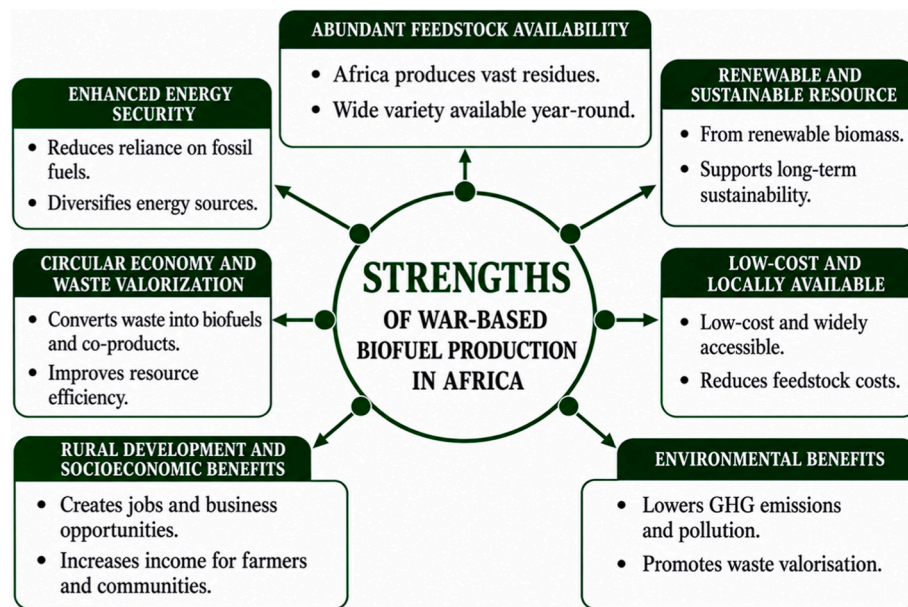


Fig. 1. Major strengths of utilizing waste agricultural residues (WAR) as renewable feedstocks for biofuel production in Africa. The schematic illustrates the key strengths and driving factors for producing biofuels from waste agricultural residues (WAR) in Africa. These strengths highlight the potential of WAR to support sustainable biofuel production, climate-change mitigation, resource efficiency, rural development through green job creation, affordable and cleaner energy production, and the transition towards a resilient, low-carbon circular bioeconomy.

production and expanding agricultural activities [64,66]. Uzoagba et al. [65] report that Africa produced over 800 million tonnes of crops in 2021, generating substantial quantities of residues in countries (especially in top economies (Table 1)) such as South Africa, Nigeria, Egypt, Algeria, Morocco, Kenya, Ethiopia, Angola, Côte d'Ivoire and Ghana. Interestingly, several studies have suggested that the continent possesses a reliable and renewable feedstock base capable of supporting industrial-scale bioenergy development. However, while the literature convincingly demonstrates resource abundance, it generally assumes that residue availability directly translates into feedstock accessibility, with comparatively limited discussion of seasonal variability, competing residue uses and collection efficiency, which may constrain actual biomass supply.

Moreover, the geographical distribution of agricultural residues is an important comparative advantage. Since agriculture remains the dominant livelihood in most rural African communities, biomass residues are generated close to farms and agro-processing facilities, thereby reducing transportation distances and associated logistics costs [18], [22], [65]. Studies consistently argue that residues from major staple crops—including maize, cassava, sorghum, yam, potato, sugarcane, plantain and cotton—are sufficiently widespread to support decentralised bioenergy systems [3,21]. This decentralization is presented as a mechanism for improving rural energy access, reducing dependence on imported fossil fuels, and strengthening regional energy security. Nevertheless, most authors focus primarily on feedstock proximity, while paying relatively little attention to the infrastructure, transport networks and institutional coordination required to sustain decentralised bioenergy systems at commercial scale.

Socioeconomic benefits represent another recurring strength of using WAR for biofuel production. Agricultural residues, previously regarded as low-value by-products, can be incorporated into biofuel value chains through collection, preprocessing, transportation and conversion activities [62,64,67]. Reports consistently suggest that these activities create employment opportunities, diversify rural incomes, and stimulate local enterprises that could contribute to poverty reduction. This perspective extends the value of WAR beyond energy generation by positioning residue-based biofuel production as a catalyst for rural economic transformation. However, much of the available evidence remains

predictive rather than empirical, with relatively few studies quantifying long-term employment outcomes or assessing whether economic benefits are equitably distributed among smallholder farmers and rural communities [14].

Environmental sustainability is another major strength identified across different studies (Sikiru et al., 2024; [2], [14], [20], [68]). Post-harvest losses and agro-processing by-products, including husks, peels, broken grains, rejected fruits and other organic wastes, represent valuable feedstocks for producing biofuels [2,66,68]. Their utilization reduces open-field burning, decreases landfill disposal, mitigates GHG emissions, and promotes more efficient waste management [2,62,65]. Clearly, agricultural residue valorisation is central to the circular bioeconomy by converting previously discarded biomass into renewable energy products. Despite this broad consensus, the literature generally evaluates environmental benefits qualitatively, with comparatively limited life-cycle assessments that comprehensively account for emissions associated with residue collection, transportation, processing and conversion technologies.

Overall, the waste agricultural residues offer significant technical, environmental and socioeconomic advantages for sustainable biofuel production in Africa. Their abundance, favourable biochemical composition, geographical accessibility, potential to support rural livelihoods and contribution to circular resource management collectively position WAR as one of the continent's most promising renewable energy resources. Nevertheless, the potential application of WAR-based biofuel remains largely optimistic, with insufficient critical examination of logistical constraints, competing biomass uses, infrastructure limitations, and long-term economic viability. Addressing these gaps through integrated techno-economic and life-cycle assessments would provide a more balanced understanding of the practical potential of WAR-based biofuel systems across diverse African contexts.

5.2. Weaknesses of biofuel production from WAR in Africa

Despite the considerable potential of waste and agricultural residues (WAR) as sustainable biofuel feedstocks, their large-scale production across Africa remains constrained by interconnected technical, economic, institutional and logistical challenges (Fig. 2). These weaknesses

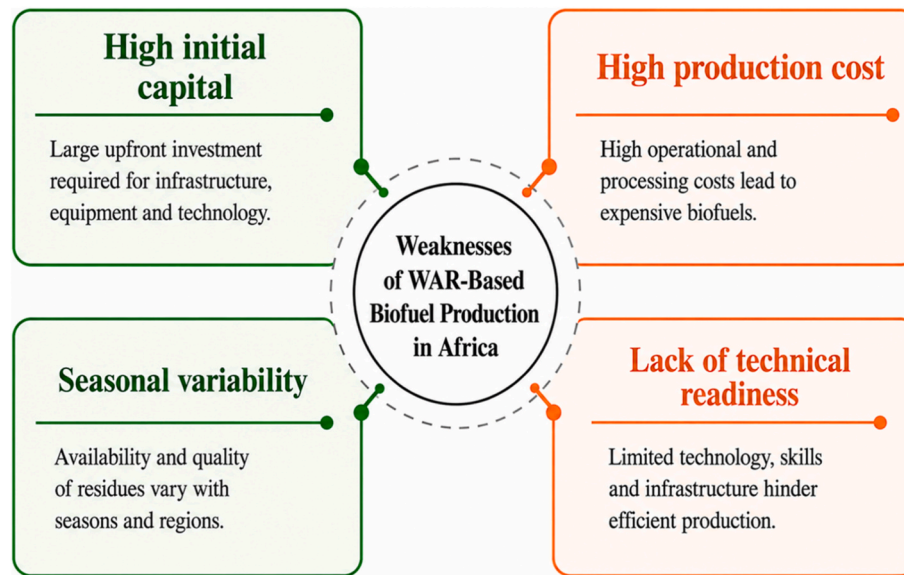


Fig. 2. Challenges/weaknesses associated with waste agricultural residue (WAR)-based biofuel production in Africa. The major challenges limiting the large-scale deployment of WAR-based biofuel production in Africa include high initial capital investment, seasonal variability in residue availability, limited technical readiness and high production costs. These constraints hinder the economic viability and widespread commercialization of WAR-based biofuel technologies.

are structural rather than isolated, collectively limiting the long-term scalability and competitiveness of WAR-based biofuel systems.

A major concern is the continued link between biofuel production and food security. With the rise in global food prices and crises, the concern of staple crop diversion towards energy markets has gained increased attention, particularly in nations where food security is already fragile [69]. Although residue-based biofuels are widely promoted as a solution to the food-versus-fuel debate, evidence suggests many limiting challenges to its implementation in many African countries. Several biofuel programmes, particularly in West and East Africa, continue to rely partly on food crops such as sugarcane, cassava and sorghum, thereby maintaining competition between energy production and food systems [70,71]. Moreover, agricultural residues themselves perform essential ecological and socio-economic functions within smallholder farming systems, including livestock feeding, soil nutrient recycling, mulching, and household processing activities. Their diversion towards biofuel production therefore could create indirect trade-offs that may compromise agricultural productivity and rural livelihoods if residue extraction exceeds sustainable levels. This challenge is exacerbated by weak policy coordination between the agriculture, energy and environmental sectors, alongside fragmented land governance systems that intensify competition for land, water and labour resources [69,72]. In addition, complex land tenure systems in most African nations further compound competition for land, resulting in either stalled or terminated projects [70,72]. Collectively, these findings suggest that the sustainability of WAR-based biofuels depends not only on feedstock availability but also on integrated resource management.

Feedstock availability presents another significant limitation. Agricultural residues exhibit pronounced seasonal fluctuations in both quantity and quality, reducing the reliability of year-round WAR supply. Also, variations in moisture content—in some cases the moisture content fluctuates significantly between seasons, ranging from about 10% to 60%—substantially affect biomass energy density while increasing the costs of transportation, drying and storage [66]. For instance, empirical evidence from Ethiopia demonstrates that seasonal changes in residue and water availability reduced the proportion of households capable of operating biogas digesters by approximately 62% between wet and dry seasons [73]. Similar challenges have been reported across Sub-Saharan Africa, where WAR biomass is generated during relatively short

harvesting periods and is geographically dispersed, making continuous industrial-scale operation difficult [74]. Consequently, biofuel facilities require substantial investments in feedstock characterization, storage infrastructure, feedstock logistics and supply-chain management to maintain operational continuity, thereby increasing production costs and reducing economic efficiency. Economic viability remains one of the most frequently identified barriers to WAR-based biofuel production.

Moreover, unlike first-generation biofuels derived from edible starch or sugar crops, WAR has complex structural compositions that require expensive pretreatment technologies before biochemical or thermochemical conversion can occur [62]. Beyond processing costs, fragmented feedstock sources, inadequate transport infrastructure and dependence on imported technologies further elevate production expenses [37,75]. Economic assessments indicate that, although WAR-based biofuel projects may generate positive net present values under favourable assumptions, their profitability remains highly sensitive to feedstock accessibility, technological requirement and policy incentives [76]. As a result, production costs often exceed prevailing fossil fuel prices, limiting market competitiveness without sustained government support through subsidies, tax incentives or carbon-pricing mechanisms.

High capital investment requirements further constrain the commercial deployment of WAR-based biofuel. The establishment of large-scale WAR-based biofuel facilities requires substantial upfront expenditure on processing plants, storage systems, transport infrastructure and supporting utilities. For example, feasibility assessments estimate that constructing a residue-to-ethanol facility requires approximately US \$46 million in capital investment, in addition to significant operating costs per unit of ethanol produced [66,77]. Such financial demands present considerable barriers in many African economies, where long-term financing is limited, lending rates remain high, and access to affordable capital is constrained [62]. Financial institutions also perceive bioenergy projects as high-risk investments because of technological uncertainty, underdeveloped business models, inconsistent policy implementation, and limited evidence of successful project recovery [37,75]. Weak government guarantees, insufficient public investment and inadequate infrastructure—including unreliable electricity networks, poor road systems, and limited storage capacity—further undermine investor confidence and delay project implementation.

Overall, the weaknesses of WAR-based biofuel production extend beyond technological limitations to encompass institutional, economic and governance challenges. Feedstock seasonality, competing residue uses, high production costs, limited financing and fragmented policy frameworks reinforce one another, restricting the scalability and long-term sustainability of the sector. Addressing these weaknesses will therefore require integrated policy frameworks, technological innovation, investment in WAR logistics and infrastructure, as well as financial mechanisms that reduce investment risks while promoting sustainable residue management.

5.3. Opportunities of biofuel production from WAR in Africa

Waste agricultural residue-based biofuel production has been identified as presenting strategic opportunities (Fig. 3) to accelerate Africa's transition towards a low-carbon and circular bioeconomy. Rather than relying solely on feedstock abundance, recent studies argue that the continent's comparative advantage lies in integrated, adaptable technologies, supportive policy frameworks, and expanding international demand for sustainable fuels. These drivers could position Africa as a potential leader in second-generation biofuel production, although their effectiveness depends on coordinated technological, institutional and market development.

Conversion technological advancement has emerged as one of the most influential factors improving the viability of WAR-based biofuel systems. Recent advances in WAR-based biomass pretreatment technologies, co-digestion strategies and integrated biorefinery systems have substantially improved the viability of WAR-based biomass conversion efficiency towards reducing production costs [17,62,65]. Beyond process innovation, techno-economic assessments have become essential decision-support tools, enabling the identification of conversion pathways best suited to African feedstocks and the existing infrastructure [65,78]. Furthermore, improvements in enzyme engineering, microbial biotechnology and synthetic biology have expanded the range of residues that can efficiently be converted while reducing dependence on expensive chemical pretreatments. Importantly, several studies suggest that integrating biofuel production with the manufacture of high-value biochemicals, including lactic acid and other platform chemicals,

enhances economic resilience by diversifying revenue streams rather than relying exclusively on fuel markets.

Policy interventions are equally recognised as critical catalysts for commercial deployment. Evidence from South Africa, Mozambique and Ghana demonstrates that blending mandates create stable markets that encourage long-term investment in biofuel production [72,75,79]. However, the literature emphasises that mandates alone are insufficient. Their effectiveness increases when complemented by fiscal incentives, concessional financing and infrastructure support, which collectively reduce investment risks and improve private-sector participation. Such policy packages also facilitate the establishment of organised residue supply chains, thereby strengthening the transition from food-based feedstocks to waste agricultural residues, as well as addressing persistent food-versus-fuel concerns.

Africa's extensive WAR resource base provides another major opportunity for the implementation of sustainable biofuel production. The continent generates approximately 102.256 Gt of fresh agricultural residues annually, much of which remains underutilised despite its considerable energy potential [17,65]. Agricultural residues, food waste, municipal solid waste and industrial wastewater can be converted into bioethanol, biodiesel, biogas and other bio-based products, simultaneously improving waste management and enhancing resource efficiency [36,70,80–82]. The integration of bioenergy production with co-products such as biochar and bioplastics further underscores the circular economy concept by increasing environmental benefits and creating additional economic value across agricultural and industrial sectors. Consequently, WAR valorisation would contribute not only to renewable energy generation but also to greenhouse gas mitigation, sustainable waste management (through decreases in open burning and landfill disposal), and progress towards the fulfilment of multiple Sustainable Development Goals (SDGs).

International market dynamics further underscore the strategic importance of residue-based biofuels. Increasing global commitments to decarbonisation have generated growing demand for certified low-carbon fuels, particularly within European markets, where sustainability verification has become a prerequisite for market access [72,78]. Modelling studies estimate that Africa possesses a residue-based bioethanol production potential of approximately 207.127 EJ, substantially

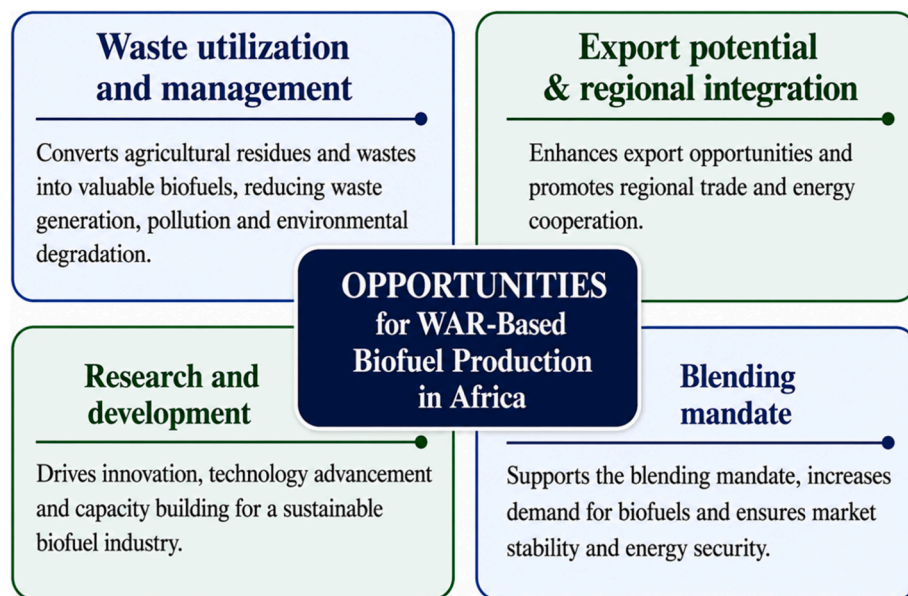


Fig. 3. Opportunities for waste agricultural residue (WAR)-based biofuel production in Africa, showing the major opportunities associated with converting waste agricultural residues (WAR) into biofuels in Africa. These include improved waste utilization and management, enhanced export potential and regional integration, increased research and technological innovation, and the implementation of biofuel blending mandates. These opportunities support greenhouse gas emission reduction, resource efficiency, energy security, sustainable rural development, and the transition towards a low-carbon circular bioeconomy.

exceeding its current transport fuel demand of approximately 7.95 EJ [17,65,74,75]. This surplus production potential presents opportunities for export, foreign exchange generation, reduced dependence on imported petroleum products and enhanced long-term energy security. Moreover, several studies suggest that surplus WAR resources could simultaneously support decentralised electricity generation, thereby improving rural electrification while strengthening national energy systems.

In summary, the literature has presented different opportunities associated with WAR-based biofuel production that extend well beyond renewable fuel generation. Technological innovation, favourable policy environments, abundant biomass resources and expanding international markets collectively create a strong foundation for sustainable bio-energy development in Africa. Nevertheless, realising these opportunities will require coordinated investment in technological capacity, government support and efficient feedstock logistics. Without these complementary interventions, the continent's considerable WAR potential is unlikely to translate into large-scale commercial biofuel production.

5.4. Threats to biofuel production from WAR in Africa

Despite the significant potential of waste and agricultural residues (WAR) as sustainable feedstocks for biofuel production, multiple environmental, economic, biological and institutional threats continue to constrain their long-term viability in Africa. These threats (Fig. 4) ultimately reduce feedstock availability, increase production costs and limit the scalability of residue-based biofuel technologies.

Climate change emerges as one of the most critical threats to sustainable WAR-based biofuel production. The predominance of rain-fed agriculture across Africa makes WAR availability highly sensitive to changing climatic conditions [83,84]. Increasing temperature extremes, prolonged droughts, erratic rainfall patterns and more frequent extreme weather events have been consistently associated with declining crop productivity, thereby reducing the quantity of agricultural residues available for biofuel production. Beyond lowering WAR biomass yields, climatic variability also compromises residue quality by increasing

moisture content during harvesting and storage. Elevated moisture accelerates microbial degradation, reduces storage stability, and complicates transportation and processing, thereby increasing conversion costs. Climate projections further suggest that these vulnerabilities are likely to intensify over the coming decades, indicating that climate adaptation strategies must become integral to future biofuel development.

Anthropogenic land-use changes could further compound climate-related pressures. Although biofuels are promoted as a renewable energy solution, the expansion of dedicated biofuel cropping through deforestation or the conversion of natural ecosystems can undermine environmental sustainability by accelerating biodiversity loss, ecosystem degradation and GHG emissions [72]. Such trade-offs demonstrate that the sustainability of WAR-based biofuels depends not only on technological efficiency but also on responsible land-use governance that prioritizes residue utilization over the conversion of natural landscapes.

Economic risks also represent a major constraint to the competitiveness of African biofuel industries. Biofuel markets are strongly influenced by fluctuations in global agricultural commodity prices, fossil fuel prices and international climate policies [72]. Declining fossil fuel prices reduce the economic attractiveness of biofuels, while volatile crop markets could influence agricultural residue prices, where applicable, and feedstock availability. These external market forces expose African producers to financial uncertainty, despite local resource abundance. Furthermore, achieving economies of scale requires substantial investments in large processing facilities, transport infrastructure and advanced conversion technologies. Competition for agricultural residues from livestock feed, soil amendment and industrial applications could further increase feedstock costs, reducing the economic competitiveness of residue-based biofuels [17]. Currency instability across many African economies exacerbates these challenges by increasing the cost of importing the specialised technologies, enzymes and processing equipment required for efficient biofuel production [85].

Biological threats similarly undermine sustainable feedstock supply. Crop pests, diseases, rodents and weeds substantially reduce agricultural productivity and consequently decrease both crop yields and residue

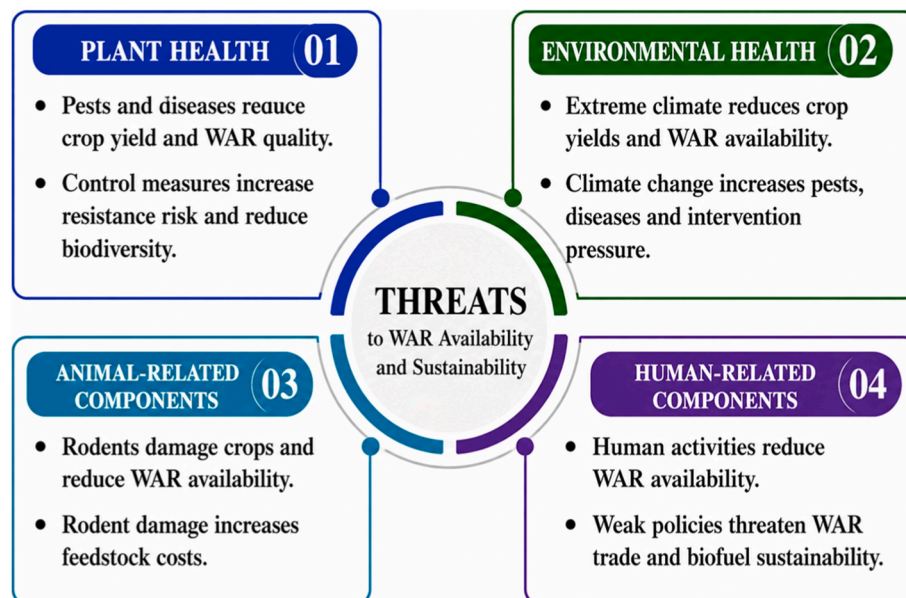


Fig. 4. Schematic overview of factors that could threaten waste agricultural residue (WAR) availability and sustainability using a One Health approach. The One Health approach (OHA) recognizes the interconnectedness of plant, human, animal and environmental health in influencing the sustainability of WAR-based biofuel production. Within the OHA framework, the major threats to the long-term sustainability of WAR-based biofuel production include environmental challenges, such as soil nutrient depletion and climate change; human anthropogenic activities; and animal-related threats (particularly damage caused by pest rodents). Tackling these interconnected risks is essential for ensuring the sustainability of WAR-based biofuel systems.

generation. Diseases, pests, weeds and other abiotic stressors account for about 35% pre-harvest losses [86]. For example, the African continent provides about 27% of global cereal production, with uncontrolled pests and weeds leading to significant losses. Similarly, about 48% of the yield losses in maize fields have been attributed to rodent-inflicted crop destruction in Sub-Saharan Africa [87]. Yield losses caused by these biological stressors not only reduce biomass availability but may also compromise residue quality for conversion into biofuels. Farmers often respond through increased pesticide use and disease management interventions [84], which elevate production costs and might contribute to pesticide resistance and broader environmental concerns. These findings suggest that sustainable residue availability is intrinsically linked to resilient agricultural systems capable of effectively managing biological risks while maintaining crop productivity.

Institutional and governance challenges constitute another significant barrier to scaling WAR-based biofuel production. Weak policy implementation, fragmented institutional coordination and inconsistent regulatory frameworks have limited investment and commercialization across several African countries [72]. The literature consistently highlights that policy uncertainty discourages long-term investments and restricts regional biofuel trade. Addressing these governance limitations requires stronger collaboration among governments, research institutions, industry, farming communities and international partners to establish coherent policies that support sustainable WAR utilization and market development.

Collectively, these threats illustrate that the sustainability of WAR-based biofuel production cannot be addressed through technological innovations alone. Instead, the evidence supports adopting an integrated One Health framework (Fig. 4) that recognizes the interconnectedness of environmental, agricultural, human and animal health systems [88,89]. Such an approach enables climate adaptation, sustainable land management, integrated pest management, resilient agricultural practices and coordinated policy development to be implemented simultaneously. By addressing these interconnected threats holistically, African countries can strengthen the resilience of residue-based biofuel systems while advancing renewable energy production, environmental sustainability and food security. In addition, government institutions need to work closely with other institutions globally, and with academia, industries, communities and other stakeholders, to ensure threats to sustainable biofuel production are addressed [65].

5.4.1. Land-use conflicts, rural inequalities, and impacts on smallholder farmers

Other threats to WAR-based biofuel production include land-use conflicts, rural inequalities and impacts on smallholder farmers. Transitioning to biofuels derived from WAR in Africa offers considerable opportunities for renewable energy generation and rural economic development. However, without appropriate governance and sustainability regulations, the transition might also generate significant socio-economic risks, particularly for smallholder farmers and rural communities. These risks are primarily associated with insecure land tenure, competition for agricultural residues, and the concentration of economic benefits among large commercial stakeholders [20,69,90,91]. A major concern is the displacement of traditional residue uses. Agricultural residues such as maize stover, rice straw and sugarcane bagasse are often regarded as waste, yet they perform essential functions within smallholder farming systems. Rural households commonly use these residues as livestock feed, organic soil amendments, mulch for moisture conservation, and household cooking fuel. Large-scale diversion of these materials to biofuel production might therefore create competition between biofuel production and existing agricultural and household needs. Excessive residue removal could undermine smallholder farming. Land tenure insecurity represents another critical challenge. In several African countries, including South Africa and Malawi, many smallholder farmers operate under customary or informal land tenure systems with

limited legal protection. In such contexts, the commercial expansion of WAR-based biofuel industries may encourage large-scale land acquisitions, whereby private investors gain control of fertile agricultural land at the expense of local communities. This process can displace vulnerable households, reduce access to productive land resource and heighten existing socio-economic inequalities. Moreover, historical experiences also demonstrate the vulnerability of smallholders to market volatility. These experiences highlight the importance of developing diversified and resilient biofuel value chains, rather than exposing rural producers to highly volatile commodity markets.

Crop residues play a vital role in maintaining soil organic carbon, supporting microbial activity, reducing erosion and enhancing nutrient cycling. Excessive residue removal for biofuel feedstocks can significantly reduce soil fertility, particularly among resource-constrained smallholders who cannot afford adequate fertilizer inputs. The progressive depletion of soil organic matter might ultimately reduce crop productivity, threaten food security and diminish the sustainability of agricultural systems [92]. Also, competition for freshwater resources poses an additional socio-economic risk. The expansion of associated bioenergy infrastructure might increase water demands in water-scarce regions, thereby affecting vulnerable smallholders when commercial biofuel operations receive priority access. This will result in heightened water insecurity, reduced agricultural productivity, and further marginalize rural communities. Hence, integrating these social safeguards into national bioenergy policies will be essential for achieving an inclusive and sustainable bioeconomy.

5.4.2. Biofuel market competitiveness, pricing volatility, and consumer acceptance

The competitiveness of WAR-based biofuels remains relatively weak compared with conventional fossil fuels. One of the principal reasons is the continued subsidization of petroleum products in many African countries, which artificially lowers the retail prices of gasoline and diesel, and thereby reduces the economic attractiveness of renewable alternatives. Consequently, second-generation biofuels derived from agricultural residues often struggle to achieve price competitiveness without external support [93]. Production costs are further elevated by the capital-intensive nature of large-scale WAR-based production. Also, the absence of a supportive and predictable policy model further weakens market competitiveness. In many African countries, inconsistent biofuel policies, weak implementation of blending mandates, limited fiscal incentives and the absence of carbon pricing mechanisms discourage long-term private investment. Without renewable tax exemptions, production subsidies and carbon credit incentives, many WAR-based biofuel projects remain economically viable only through government support or international development financing.

Pricing volatility and uncertainty represents another major challenge to the commercialization of WAR-based biofuels. Market dynamics within the energy sector also significantly influence biofuel competitiveness [93]. Declining global crude oil prices reduce the relative cost advantage of renewable fuels, making fossil fuels more attractive to consumers and limiting demand for biofuels. In addition, macroeconomic factors (like exchange rate volatility, inflation, rising transportation costs and high borrowing costs) further increase production expenses across the biofuel value chain. These uncertainties complicate long-term financial planning, discourage private-sector investment and increase the perceived risks for financial institutions considering investments in bioenergy projects [93].

Consumer acceptance remains a critical determinant of market expansion for WAR-based biofuels. Across much of Africa, public awareness of the environmental, economic and energy security benefits of biofuels remains limited [14]. This knowledge gap contributes to cautious consumer attitudes and slows the adoption of biofuel blends. Similarly, many consumers remain uncertain about engine compatibility, fuel quality, vehicle performance and potential maintenance costs associated with biofuel use. Public perception is further affected by the

widespread association of biofuels with food security risks and land-use competition. This misconception obscures the key sustainability advantage of WAR-based biofuels, namely their reliance on non-food biomass that would otherwise be discarded [14].

Overcoming these interconnected barriers requires coordinated policy, institutional and market-based interventions. Governments have a central role in creating an enabling environment that enhances the competitiveness of WAR-based biofuels. Reducing market uncertainty will also require transparent pricing mechanisms, long-term feedstock supply agreements, guaranteed purchase contracts, and carbon pricing or carbon credit schemes that recognize the environmental benefits of residue-based biofuels. Equally important is strengthening consumer confidence through public education campaigns that can improve public perception and encourage the wider consumption of biofuel.

5.4.3. Investment risks affecting WAR-based biofuel investor confidence

Despite the growing potential of WAR-based biofuels, several investment risks continue to discourage large-scale private investment across Africa. These investment risks include policy and regulatory uncertainty, the impact of climate change, feedstock supply risks, technology risks, market risks, financial and currency risks, as well as infrastructure risks, which remain some of the most significant barriers [94]. Climate change further increases uncertainty by affecting agricultural productivity and WAR yields. Investors therefore require confidence that sufficient feedstock quantities can be secured through long-term contractual arrangements. Technology risk is particularly relevant for second-generation lignocellulosic biofuel technologies. Equipment failures, low conversion efficiencies and maintenance challenges can substantially increase operating costs and delay returns on investment. Market risk also influences investment decisions. Where fossil fuels remain heavily subsidized, biofuels often struggle to compete economically without complementary policy support. Financial and currency risks present additional challenges resulting from high interest rates, inflation and exchange rate volatility, and limited access to long-term credit significantly increases financing costs for African renewable energy projects [94].

6. Financing models for war-based biofuel production

The commercialization of biofuels from waste agricultural residues (WAR) in Africa is constrained primarily by the high upfront capital requirements [14]. Although the continent possesses abundant agricultural biomass resources and an expanding renewable energy market, private investors remain cautious because of technological uncertainties, inconsistent policy environments, feedstock supply risks, and long investment payback periods. Consequently, the sustainable growth of the WAR biofuel sector depends on innovative financing and targeted economic incentive mechanisms.

A diversified financing strategy is essential because no single funding mechanism can adequately support the development of Africa's biofuel industry [95]. Public-private partnerships (PPPs) represent one of the most suitable financing models, allowing governments to share investment risks with private developers [95]. Blended finance has also emerged as an effective mechanism for renewable energy investments in developing economies. This approach combines concessional financing from multilateral development banks, climate funds and development finance institutions with commercial private investment. With this arrangement, part of the risk is absorbed through concessional loans or first-loss capital. Institutions such as the African Development Bank (AfDB), the World Bank, the Green Climate Fund (GCF), the Global Environment Facility (GEF) and the International Finance Corporation (IFC) can play significant roles towards financing large-scale WAR biofuel infrastructure on the Africa continent.

Other potential financing models for WAR-based biofuel production that offer a promising financing avenue are green bonds, climate bonds, carbon finance and community-based financing [95]. These debt

instruments could enable governments and private companies to raise capital specifically for environmentally sustainable projects. The financing models could supplement operational revenues, shorten investment payback periods and enhance project profitability. As the global demand for environmental, social and governance (ESG) investments continues to expand, African biofuel projects with measurable GHG reductions and circular economy benefits could increasingly access international capital markets through certified green financing mechanisms. Interestingly, emerging Article 6 mechanisms under the Paris Agreement further create opportunities for African countries to monetize verified emission reductions through international carbon trading.

6.1. Economic incentives to attract biofuel investment

Potential economic incentives for WAR-based biofuel projects on a large scale include capital investment subsidies, tax incentives, low-interest loans, government-backed credit, feed-in tariffs, performance-based incentives and carbon pricing policies [94]. Capital investment subsidies can offset the exceptionally high initial costs of constructing biorefineries, feedstock collection centres and conversion facilities. Tax incentives, including tax holidays, accelerated depreciation allowances, reduced corporate income taxes, import duty exemptions on biofuel equipment, and value-added tax (VAT) exemptions, can significantly reduce operating costs and improve investor returns [96]. Similarly, low-interest loans and government-backed credit guarantee schemes can improve access to affordable financing by reducing borrowing costs and mitigating lender risk. Furthermore, feed-in tariffs and mandatory biofuel blending targets could provide the needed guaranteed market demand, thereby reducing market uncertainty. Likewise, carbon pricing policies might improve the relative competitiveness of biofuels by internalizing the environmental costs of fossil fuels. These policies can significantly enhance the long-term economic viability of WAR-based biofuel projects. Importantly, stable long-term purchase agreements between governments, private stakeholders and biofuel investors could increase revenue certainty and improve project bankability. These incentives are particularly important during the initial years when projects are recovering large capital investments.

7. SMART implementation roadmap

The application of the specific, measurable, achievable, relevant and time-bound (SMART) framework provides a structured approach for translating the SWOT analysis of WAR-based biofuel production into actionable strategies. Given Africa's commitment to achieving net-zero GHG emissions, SMART goals offer a practical mechanism for aligning policy objectives with measurable outcomes, facilitating performance monitoring, investment decisions and long-term sustainability. Integrating financial feasibility, cost-benefit analysis and environmental performance indicators further strengthens the framework by ensuring that biofuel initiatives are both technically and economically viable.

7.1. Specific and measurable goals

Clearly defined and quantifiable targets are fundamental to successful biofuel implementation. These targets are also expected to align with the United Nations Sustainable Development Goals (SDGs) or initiatives. For Africa, specific objectives should prioritize increasing the utilization of WAR for biofuel production while reducing environmentally harmful disposal practices such as open burning and landfilling. Redirecting approximately 20% of available WAR toward biofuel production represents a practical benchmark that could substantially improve biomass resource efficiency.

Production targets should also be aligned with national biofuel blending mandates, with an initial achievable objective of replacing at least 2% of liquid transport fuels through sustainable biofuel production. Currently, many African countries only have specific targets for the

blending of liquid fuels with gasoline [14] but not much on the expected number of jobs to be created, and no envisaged rural and project outcomes. Beyond biofuel generation and blending efforts, measurable indicators should encompass broader and specific national socioeconomic targets or outcomes, including employment creation, rural income generation, poverty reduction and economic diversification. Current policies in many African countries primarily emphasize fuel-blending targets while paying limited attention to quantifiable indicators of social and economic development. Consequently, future policy frameworks should incorporate explicit metrics for job creation, household income improvement, rural industrialisation, greenhouse gas mitigation, carbon sequestration, and reductions in WAR biomass burning. Clear environmental goals for aspects such as the level of carbon sequestration, expected greenhouse gas (GHG) reduction, and reducing waste biomass burning and landfilling to enhance a healthy environment need to be incorporated into the overall goal. Furthermore, sustainable feedstock management should be supported through localized, contract-based supply systems that prioritize non-food agricultural residues, thereby minimizing competition with food production and enhancing long-term feedstock security.

7.2. Achievable goals

The feasibility of WAR-based biofuel production in Africa depends on setting realistic implementation targets that reflect existing technological, infrastructural, and financial capacities. Current evidence suggests that decentralised, small-to medium-scale biorefineries utilizing locally available feedstocks—including sugarcane bagasse, rice straw, cassava residues, potato waste, molasses and corn cobs—represent the most attainable pathway during the early stages of industry development. Locating processing facilities near biomass sources would reduce transportation costs, improve feedstock logistics, and enhance overall production efficiency. Achievable policy objectives should include effective enforcement of biofuel blending mandates, improved incentives for private-sector investment, and policies promoting the conversion of agricultural residues that would otherwise be burned or left to decompose. For instance, implementing blending regulations requiring a minimum biofuel share of 2% in petrol and 5% in diesel could potentially contribute to reducing reliance on imported petroleum fuels, provided that appropriate policy frameworks, infrastructure, and enforcement mechanisms are in place. Such interventions could simultaneously support renewable energy production, stimulate rural economies, and create employment opportunities. In addition, key achievable targets include infrastructure development, technological improvement and rural community development programmes through local waste-to-energy businesses. Achieving these goals could be limited by low technological readiness and investment, since high initial capital costs are required in this regard. Poor policy implementation could be another critical bottleneck in the execution of WAR-to-fuel projects. Together, different reviews identify several barriers that may limit successful implementation, including high capital investment requirements, inadequate technological readiness, underdeveloped logistics infrastructure and inconsistent policy enforcement. These constraints indicate that achieving large-scale commercialization will require sustained investment in technological innovation, infrastructure development, and institutional capacity building.

7.3. Relevance and time-bound targets

The relevance of WAR-based biofuel development lies in its capacity to simultaneously address multiple development priorities, including energy security, affordable energy access, environmental sustainability, rural economic transformation and reduced dependence on imported fossil fuels. These priorities also align with the United Nations (UN) sustainable development goals. By converting agricultural residues into renewable fuels, African countries can strengthen circular economy

practices while improving waste management and reducing greenhouse gas emissions.

Time-bound implementation strategies are essential for evaluating progress and maintaining policy accountability. The literature recommends phased targets comprising short-, medium- and long-term milestones. Short-term objectives could focus on diverting more than 19% of available WAR to biofuel production before 2030, while medium-term goals should support national bioenergy strategies, including projections for increased renewable energy contributions and expanded employment opportunities across the bioenergy sector. Present projections show that Africa is expected to gain an estimated 4.5 million potential employment opportunities by 2030 through renewable and bioenergy development. Long-term targets extending to 2050 should prioritize large-scale production, increased transport fuel substitution/blending, and substantial decarbonisation of national energy systems. This is in line with the World Bioenergy Association forecasts of 42 to 69 Exajoule (EJ) of global energy from WAR, with a significant proportion leaning towards African WAR-to-bioenergy implementation.

Country-specific projections illustrate the practicality of these timelines. For example, Nigeria aims to integrate WAR into its 2030 bioenergy strategy, while Ghana has established ambitious renewable fuel targets within its transport sector. South Africa's projections indicate that utilizing approximately 50% of available WAR could potentially replace up to 70% of current fossil fuel consumption by 2050, contributing significantly to national decarbonisation objectives. Likewise, recent initiatives under Egypt's Vision 2030 reflect a strategic transition toward the sustainable valorisation of WAR through bioenergy development and improved waste management. The strategy targets the generation of 45% of the nation's electricity from renewable sources by 2028 and aims for clean energy to contribute 42% of the country's total energy mix by the end of the decade. These ambitious targets underscore the growing role of WAR valorisation in supporting Egypt's energy transition, enhancing resource efficiency and promoting long-term environmental sustainability [97]. Similarly, bioethanol investment assessments in Eswatini suggest economically attractive returns within five to ten years, underscoring the potential of competitive WAR-based energy costs and highlighting the commercial viability of appropriately designed WAR-based biofuel projects. The findings project WAR-to-biofuel implementation in countries like Ghana, Nigeria and South Africa will meet some of their bioenergy needs by 2050 [14, 43].

7.4. Technical readiness for WAR-based biofuel development

Technical readiness remains a critical determinant of successful biofuel commercialization across Africa. The continent's leading economies—including South Africa, Nigeria, Egypt, Morocco, Kenya, Ethiopia, Algeria, Angola, Côte d'Ivoire and Ghana—possess different levels of technological capability, policy support and WAR biomass availability that collectively position them as potential leaders in WAR-based biofuel production. When the economic practicality of biofuel production in these countries is demonstrated, large-scale industrial production could be achieved through private-sector investment. However, long-term sustainability depends on establishing reliable feedstock supply chains, strengthening stakeholder collaboration, and expanding financial incentives that encourage industrial investment. A well-expanded incentive structure and stakeholder involvement are necessary to this end.

Several countries have introduced national biofuel policies and incentive frameworks to accelerate sector development. Nigeria's Biofuel Policy and Incentives Programme promotes bioethanol and biodiesel production based primarily on sugarcane, cassava, palm oil and jatropha, although implementation has fallen short of its E10 blending ambitions [98]. Ghana's National Energy Policy targets a 20% biofuel share in transport fuel mix by 2030 [99], while South Africa's Biofuels Industrial Strategy combines modest blending targets with broader rural

development objectives and complementary climate policies, including the introduction of a national carbon tax [14]. Despite different levels of implementation success, these initiatives demonstrate increasing institutional commitment toward a renewable energy transition.

At the continental level, the African Union Bioenergy Policy Framework provides strategic guidance for developing economically viable, environmentally sustainable and socially inclusive bioenergy systems [100]. The framework explicitly promotes the sustainable utilization of agricultural and forestry biomass, including crop residues, to enhance energy security, reduce GHG emissions, stimulate rural development and support the transition to a circular bioeconomy. It also aligns with broader African Union development agendas, including AU Agenda 2063, by encouraging member states to integrate bioenergy into national energy, agricultural, climate and waste management policies. Consequently, several African countries (as highlighted above) have incorporated bioenergy and agricultural residue valorisation into their renewable energy strategies and long-term national development frameworks, demonstrating increasing policy recognition of waste agricultural residues as a strategic resource for sustainable energy and green economic growth.

In summary, these policy instruments indicate that, although technical readiness varies across countries, Africa possesses a strong foundation upon which the large-scale commercialization of WAR-based biofuels can be developed progressively, provided that existing technological, financial and institutional barriers are effectively addressed.

8. WAR-to-biofuel production: roles, capacities and conflicts amid stakeholders

The successful development of WAR-based biofuel production in Africa depends on effective collaboration among governments, industries, farmers and research institutions [14,95]. Each stakeholder has distinct responsibilities, capacities (Table 2) and interests that can either facilitate or hinder the growth of the sector. Effective WAR-to-biofuel development requires coordinated stakeholder engagement. Governments should establish enabling policies and regulatory frameworks, industries provide the needed investment and commercialization pathways, farmers ensure a sustainable supply of WAR biomass feedstock, and research institutions drive technological innovation and capacity building (Table 2). However, conflicts might arise over land rights, residue management, pricing mechanisms, environmental sustainability, and the allocation of agricultural residues between biofuel production, livestock feeding and soil conservation. Addressing these challenges through transparent governance, equitable benefit-sharing, strong public-private partnerships and continuous stakeholder

dialogue is essential for achieving sustainable and inclusive WAR-based biofuel development across Africa.

9. Economic viability, employment, and SDG linkages

The environmental costs associated with fossil fuel dependence have accelerated the transition toward cleaner and more sustainable energy systems, with biofuels derived from waste agricultural residues (WAR) emerging as a promising alternative. Globally, more than two billion tonnes of solid waste are generated annually, with Africa contributing a significant proportion owing to its expanding population and agricultural activities. This volume is projected to exceed 9.5 billion tonnes by 2050, underscoring the urgency of adopting sustainable waste management and resource-recovery strategies [14,101]. In this context, the conversion of WAR into biofuels offers a dual environmental benefit by reducing waste accumulation while providing renewable energy (Fig. 5).

The successful implementation of WAR-to-biofuel systems depends on the integration of technological readiness, economic viability, and enabling policy frameworks. These components should operate within an adaptive management framework that incorporates continuous monitoring and feedback to optimize system performance and sustainability. Key environmental performance indicators include the net reduction in greenhouse gas (GHG) emissions, the proportion of agricultural residues diverted from open burning or landfill to biofuel production, and the associated improvements in air and water quality. These indicators provide basis the for assessing the environmental effectiveness of WAR-based bioenergy systems.

Beyond its environmental advantages, WAR-based biofuel production contributes directly to the achievement of several United Nations Sustainable Development Goals (SDGs). Most notably, it supports SDG 7 (Affordable and Clean Energy) by expanding the availability of renewable, low-carbon energy sources. Despite global progress, approximately 645 million people are still projected to lack access to electricity by 2030, with the majority residing in developing countries. Consequently, converting locally available agricultural residues into biofuels can enhance energy access, improve energy security, diversify national energy portfolios, and reduce dependence on fossil fuels while promoting rural electrification.

Waste agricultural residue valorisation also aligns strongly with SDG 11 (Sustainable Cities and Communities) by promoting sustainable waste management and improving urban environmental quality. The effective conversion of agricultural residues into biofuels diverts waste from uncontrolled disposal and open-field burning, thereby reducing air, water and soil pollution. Integrating WAR into biorefineries and

Table 2
Roles, capacities and potential conflicts among stakeholders Sources: [14,95].

Stakeholder	Primary roles	Capacities	Potential conflicts
Governments	1. Develop and enforce regulations. 2. Provide incentives & infrastructure. 3. Enable public-private partnerships.	1. Legislative authority. 2. Provide financial support. 3. National planning capabilities.	1. Policy inconsistency & weak enforcement. 2. Land-use disputes & competing priorities 3. Food security & energy development conflict.
Industries	1. Invest in processing facilities. 2. Commercialize technologies. 3. Develop supply and logistic chains 4. Create employment opportunities.	1. Access to capital. 2. Technical expertise. 3. Production technologies. 4. Market networking.	1. Compete with traditional WAR uses. 2. Marginalize smallholder farmers. 3. Unequal contract arrangements. 4. Profit-driven WAR collection & high feedstock cost.
Farmers & Farmer Cooperatives	1. Participate in feedstock collection. 2. Supply waste agricultural residues. 3. Viable WAR management practices.	1. Large WAR resources. 2. Custodian of native knowledge. 3. Instituted agricultural systems.	1. Excessive WAR removal & reduced soil fertility. 2. Compete with livestock feed requirements. 3. Disputes over WAR ownership and pricing.
Research Institutes/Universities	1. Develop conversion technologies. 2. Improve feedstock utilization. 3. Conduct sustainability evaluations. 4. Provide technical training. 5. Aid evidence-based policymaking.	1. Research network 2. Scientific expertise. 3. Innovation capacity. 4. Laboratory facilities. 5. Extension services.	1. Limited funding. 2. Weak technology transfer mechanisms. 3. Inadequate collaboration with industry. 4. Insufficient collaboration with policymakers. 5. Delay commercialization of research outcomes.

Legend: Primary roles are the key responsibilities and activities of each stakeholder in the WAR-to-biofuel value chain; while capacities are the resources, expertise, authority, infrastructure, and networks that stakeholders can contribute; and potential conflicts refer to possible competing interests, resource-use concerns, institutional constraints, or disagreements that may arise among stakeholders.

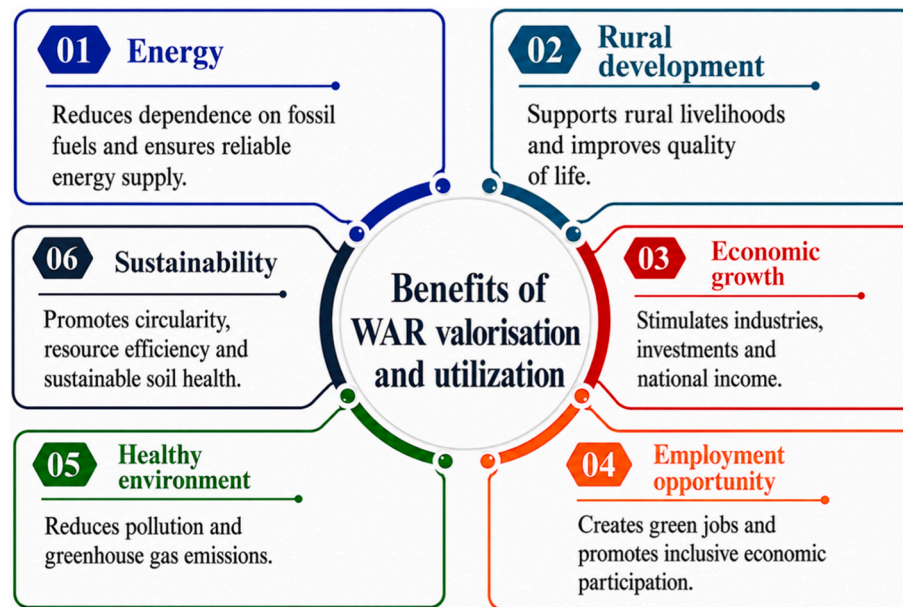


Fig. 5. Benefits of waste agricultural residue (WAR) valorisation and utilization. The schematic illustrates the key benefits of converting waste agricultural residues into valuable bio-based products, including enhanced energy security, environmental protection, rural development, employment creation, economic growth and sustainable resource utilization.

circular economy systems transforms agricultural waste into valuable bioenergy and bio-based products, creating cleaner and more resource-efficient cities while lowering environmental footprints [14].

From a broader sustainability perspective, the WAR-to-biofuel pathway represents an integrated approach to waste management, renewable energy production, and environmental conservation. Unlike first-generation biofuels, WAR utilizes non-food lignocellulosic feedstocks, thereby minimizing competition with food production and reducing concerns regarding food security. Simultaneously, it addresses multiple environmental challenges, including waste accumulation, greenhouse gas emissions and reliance on fossil fuels, while supporting circular resource utilization. Consequently, WAR-based biofuel production offers a practical strategy for advancing climate change mitigation, sustainable waste management, and low-carbon economic development, particularly across African countries with abundant agricultural residues and increasing energy demand [14].

The economic viability of renewable energy derived from WAR is becoming increasingly attractive as technological innovations continue to reduce production costs and improve conversion efficiencies. Unlike first-generation biofuels, which are often constrained by feedstock costs and food-security concerns, WAR-based biofuels utilise low-value or discarded biomass, thereby reducing feedstock costs while simultaneously addressing waste management challenges. Techno-economic assessments consistently demonstrate that, under appropriate policy, market, and technological conditions, WAR-to-biofuel systems can achieve favourable long-term economic returns [77,102–107]. These economic benefits are further strengthened by declining capital costs for biomass conversion technologies, improved process integration, and greater operational efficiencies.

Recent evidence from the International Renewable Energy Agency (IRENA) indicates that renewable energy costs have continued to decline globally, substantially improving the competitiveness of bioenergy. According to the latest Levelized Cost of Electricity (LCOE) estimates, newly commissioned utility-scale solar photovoltaic projects averaged approximately USD 0.044 kWh⁻¹ and onshore wind USD 0.033 kWh⁻¹, while electricity generated from bioenergy averaged approximately USD 0.061 kWh⁻¹ in 2023 [108]. Although bioenergy is generally more expensive than solar and onshore wind on a purely electricity-generation basis, it possesses unique advantages that are

particularly relevant for Africa. Unlike intermittent renewable technologies, bioenergy provides dispatchable baseload electricity, simultaneously manages agricultural wastes, produces valuable co-products (such as biofertilisers and biochar), and supports rural circular economies. Consequently, economic competitiveness should be evaluated beyond LCOE alone by considering avoided waste disposal costs, greenhouse gas emission reductions, improved energy security and additional revenue generated from by-products. The economic attractiveness of WAR-based biofuel production is therefore better assessed through integrated financial indicators such as the net present value (NPV), internal rate of return (IRR), benefit-cost ratio, payback period, and sensitivity analyses that account for feedstock availability, carbon pricing and energy market fluctuations [14,77]. Studies increasingly report positive NPVs and attractive IRRs for commercial-scale WAR biorefineries where feedstock supply chains are reliable and supported by enabling policies [77,109–111]. Furthermore, investment risks can be significantly reduced through public-private partnerships, carbon-credit mechanisms, concessional financing, and renewable energy incentives, making WAR-based biofuels progressively more competitive with conventional fossil fuels over the project lifetime.

Beyond direct economic returns, WAR-based biofuel production offers substantial opportunities for employment creation, rural industrialisation, and inclusive economic development across Africa (Fig. 5). The biofuel value chain is considerably more labour-intensive than fossil fuel systems because employment is generated across multiple stages, including residue collection, transportation, preprocessing, conversion, equipment maintenance, distribution and by-product utilization. This distributed value chain creates employment opportunities for farmers, transport operators, technicians, engineers, researchers, and small- and medium-scale enterprises, thereby strengthening rural economies while diversifying household income sources. Evidence from South Africa illustrates the broader employment potential of renewable energy investments. The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) reportedly created approximately 50 000 employment opportunities between 2011 and 2023, demonstrating the capacity of renewable energy investments to stimulate labour markets and local economic development. Looking ahead, IRENA projects that Africa's renewable energy sector could support approximately 300 000 jobs by 2030, driven by continued investment,

technological innovation and the expansion of renewable energy infrastructure [112]. Within this broader transition, bioenergy is expected to make a significant contribution to job creation because of its extensive upstream and downstream value chains.

The employment potential of WAR-based biofuels is particularly important given Africa's persistent unemployment challenge. Although unemployment rates remain below 15% in several African countries (2.4%, 3.9%, 4.3%, 6%, 10.8%, 11.4%, 13.1% and 13.9 in Cote d'Ivoire, Ethiopia, Nigeria, Egypt, Morocco, Algeria, Ghana and Kenya, respectively), others continue to experience exceptionally high levels, with Angola and South Africa recording unemployment of approximately 21.3% and 32.9%. In this context, the expansion of bioenergy industries represents not only an energy strategy but also a socioeconomic development pathway capable of generating sustainable livelihoods. Forecasts indicate that, in South Africa alone, bioenergy (including fuels derived from agricultural residues) could create approximately 166 000 jobs by 2050 [14]. If replicated across major agricultural economies such as Nigeria, Ethiopia, Kenya, Egypt, Ghana and Tanzania, the cumulative employment potential could be substantially greater, supporting Africa's objectives for industrialisation, poverty reduction, and low-carbon energy transition.

The socioeconomic benefits extend beyond direct employment to include increased rural incomes, improved market opportunities for agricultural residues, enhanced energy access for agro-processing industries, and stimulation of local manufacturing associated with WAR biomass-processing technologies. Since agricultural residues are produced across virtually all farming regions, decentralised bioenergy facilities can promote balanced regional development by creating employment opportunities close to WAR biomass generation areas rather than concentrating economic activity in urban centres.

The economic case for WAR-based biofuels extends well beyond fuel production. Their ability to convert low-value agricultural residues into multiple high-value products, reduce waste management costs, enhance energy security, create employment and stimulate rural industrialisation substantially strengthens their contribution to sustainable development. Consequently, future investment decisions should adopt integrated techno-economic frameworks that simultaneously evaluate financial profitability, employment generation, environmental externalities, and broader socioeconomic benefits, rather than relying solely on conventional electricity cost metrics.

10. Conclusion and future outlook

A SWOT analysis of biofuel production from waste and agricultural residues (WAR) highlights the key strengths, weaknesses, opportunities, and threats associated with this pathway, while also emphasizing the application of the SMART framework for advancing WAR-based biofuel production across Africa. The continent's growing demand for renewable energy, coupled with its expanding agricultural sector, provides a sustainable supply of WAR to support continuous biofuel production. Nevertheless, fragmented datasets, inconsistent estimation approaches, limited standardised continent-wide inventories, and the subjectivity inherent in secondary data, as encountered in the present study, can introduce substantial uncertainty into WAR estimates. Therefore, critical appraisal and validation of data quality are essential to improve the reliability and reduce the uncertainty of residue estimates. Also, high initial capital investment requirements, technological limitations and inadequate infrastructure remain significant barriers to large-scale implementation. Despite these challenges, the opportunities available substantially outweigh the constraints. Increased investment in research and development, together with strong political commitment and supportive policy frameworks, could significantly accelerate the growth of the biofuel industry across the continent.

Looking ahead, the successful expansion of WAR-based biofuel production in Africa will depend on effectively addressing existing constraints while capitalizing on emerging opportunities. Strategic

partnerships among governments, research institutions, industry and development agencies will be essential for promoting technology transfer, innovation, capacity building and the commercialization of advanced biofuel technologies. Implementing the recommendations identified in this study could unlock the full potential of WAR-based biofuel production, contributing to sustainable energy security, rural economic development, waste valorisation, greenhouse gas emission reduction, and the transition toward a low-carbon economy in Africa.

Author contributions

Isaac A. Sanusi: Conceptualization, original draft, formatting, review & editing. Abimbola E. Oluwalana-Sanusi: Original draft, formatting & review. Stella B. Eregie: Original draft, formatting & review. Emmanuel. C. Ngerem: Original draft & formatting. Boluwatife M. Daramola: Original draft & review. Olukayode O. Daramola: Original draft & review. Jeremia S. Sefadi: Review & formatting. Anathi Magadela: Original draft & review. Gbenga P. Sanusi: Original draft & review. Johnson O. Adelakun: Original draft & review. Idowu O. Oladele: Original draft & review.

Ethics approval

This is not applicable.

Declaration of competing interest

The authors declare that they have no known competing interest that could have influence the work reported in this article.

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Data availability

No data was used for the research described in the article.

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