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Review Article

Agricultural Wastes: Environmental Impacts of Open Field Burning of Crop Residues - a Review

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Abstract

The global increase in population and economic development has intensified pressure on the agricultural sector to increase production of food. In Kenya, the agricultural sector accounts for 20% of Gross Domestic Product with maize, wheat and rice being the most grown food crops. Maize is the most grown staple food and it contributes to 30% of the total agricultural activities, and serves 90% of the population. With large volumes of agricultural products produced, large volumes of agro-wastes are equally generated. Maize residues generated in Kenya vary by county, with the largest maize producing regions such as Trans Nzoia and Uasin Gishu generating approximately 4.72 MT per acre and lowest producing regions like Makueni generating 0.43 MT per acre. Disposal of crop residues has become a global problem and most agricultural economies have resorted to burning, the most convenient technique of waste management. The practice is most prevalent in India, China and Sub-Saharan Africa. This review presents an overview of burning agricultural wastes as driven by different factors. It also addresses the detrimental effects of burning on health, productivity, economy and environment, delves into the state of residue management in Kenya and associated policies and presents possible alternatives for managing agro-wastes such as composting, biochar production, animal feeds, energy production, paper manufacturing and material development. In Kenya, maize stalk residues are mainly utilized for animal feeds and large volumes are improperly disposed. Therefore, alternative solutions should be enforced including enabling innovation-based solutions.

Keywords

Agro-wastes, Burning, Economy, Environment, Health

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1. Introduction

With rapid growth in population and global economic development, there is an increasing demand to boost food production. According to the United Nations population projections, it is estimated that by 2050, the world's population will reach 10 billion [1]. The agricultural sector is therefore under pressure to increase production of food to meet population demands [2]. Agricultural wastes are referred to the residues produced after harvesting and processing agricultural products [3]. Among these wastes, a significant amount is corn straw, rice stubble, wheat residues, vegetables and fruits [4].

The agricultural sector dominates the Kenyan economy and has continued to be a key driver of sustainable development and the country's vision 2030 goals. The sector contributes to approximately 20% of Gross Domestic Product and about 27% indirectly through its linkages with other sectors. It also employs over 40% of the total population with more than 70% of the rural population [5]. The major food cereals grown in the country are maize, wheat and rice. Maize is the main staple food that serves approximately 90% of the population. The consumption of rice and wheat have also been reported to increase due to urbanization which changes the eating habits [6].

Inappropriate disposal of wastes has adverse effect on the environment, economy and society. After harvesting agricultural products, the wastes are often left on landfills or incinerated. Small quantities are utilized for animal feeds and large quantities discarded [7].

Open field burning is a common practice that has been highly adopted for waste elimination in most agricultural countries. It involves igniting agricultural residues to prepare lands for cultivation. The practice is perceived as the easiest and cheapest method of getting rid of residues [8]. Burning of crop residues is commonly practice in developing parts of Africa, South East and South Asia and is a major contributor of transboundary haze and air pollution [9].

Burning releases greenhouse emissions and particulates causing air pollution. Greenhouse gases released are Sulphur dioxide (SO_2), methane (CH_4), Carbon dioxide (CO_2), Nitrogen oxides (NO_x), Carbon monoxide (CO), and particulate matter (PM_{10}, $PM_{2.5}$). These pollutants are evidenced by the presence of smoke and haze that ultimately alters global atmospheric chemistry by absorbing solar radiation which warms the atmosphere which adversely causes global warming [10]. The emissions cause climate change, affect human health, soil fertility, economy and society. Pollutants emitted during agro waste burning is presented in Figure 1.

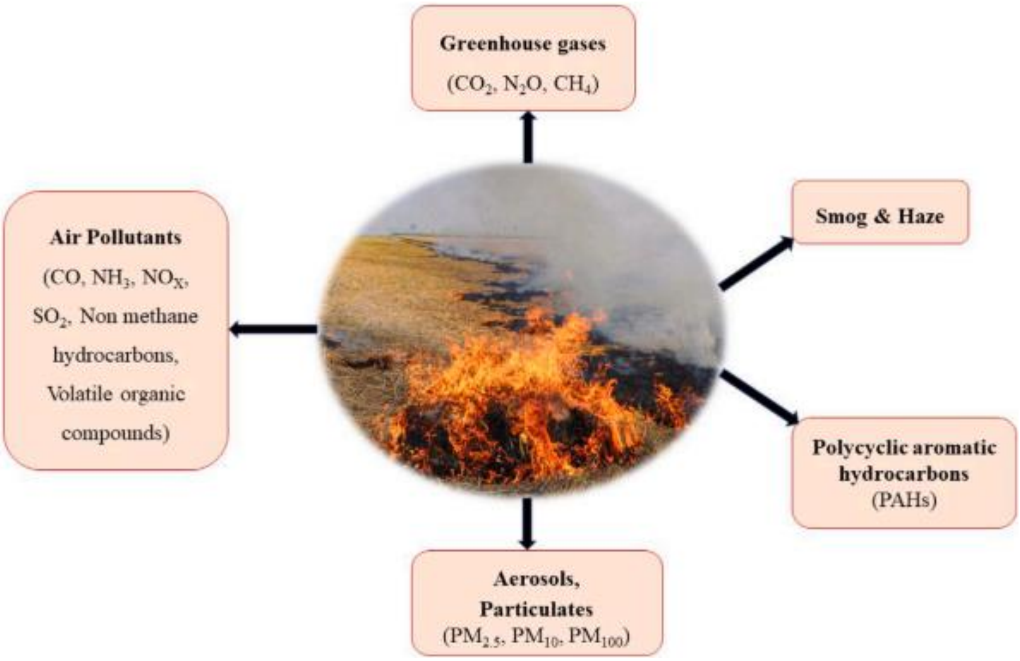

Figure 1. *Pollutants from burning of crop residues [11].*

The Kenyan agricultural sector accounts for 67% of the total greenhouse gas emissions, with food crops sub-sector contributing to approximately 10% of the total emissions resulting from activities such as convectional tillage, land use change, deforestation, flooding of paddy rice fields and open field burning of agro wastes [12]. In many countries, agricultural wastes like maize stalks and pigeon peas have been less utilized as economic source of biomass fuel and large portion is left unutilized which hinders soil preparation for next planning and pose environmental hazard due to burning [13]. Alternative management techniques of agricultural residue wastes can reduce emissions and enhance economic growth [9].

1.1. State of Agro- Waste Burning in Kenya

Maize farming in Kenya was first introduced by the Portuguese around 16th century and has become the main staple food [14]. Maize provides nutrition, food security, and generate income to farmers. As at 2022, It was estimated that maize was grown in approximately 2.196 million hectares of land with an estimated annual production of 3.897 million tonnes and benefitted around 3 million farmers [15]. Maize is also reported to account for approximately 27% of the total value of primary agricultural products in Kenya [16]. Rice and wheat are other most grown cereals in Kenya and their production has increased overtime due to urbanization and change in eating habits [17].

Despite its utilization as animal feeds, most residues still remain unmanaged. A study conducted in Mt Kenya regions reported that burning of crop residues is relatively rare and farmers effectively use crop residues to enhance soil fertility, as animal feeds and source of fuel [18]. In Western Kenya, most residues are also utilized as animal feeds [19]. Maize production in Uasin Gishu, Trans Nzoia and Nandi are high as most people practice large-scale farming. Maize production in Machakos, Embu and Kitui regions is low compared to Rift Valley The crop residues from these regions are used are livestock feed while the rest is disposed by burning [20, 21]. In 2023, the total quantity of maize residue produced across the country was reported to be 8.82 million MT with the top six maize producing counties accounting for 51%. In Makueni County, maize residues yields at 0.43 MT per acre and 4.72 MT per acre in Trans Nzoia County [22]. This further confirms that crop residue burning is most likely to be more pronounced in regions with high production as presented in Figure 2.

Figure 2. *Pictures taken in Uasin Gishu county of maize stalk burning.*

Figure 3. *Fires Detected by VIIRS in Kenya between 2012-2020 [23].*

Although burning of agro-waste is not explicitly documented in Kenya, a study conducted to characterize agricultural fires reported presence of vegetation fires between 2012-2020 as presented in Figure 3. The detected fires of crop land were reported to be 23% although the specific crop residues burned could not be identified [23].

1.2. Policy Landscape on Agricultural Residue Management in Kenya

Several policies have been enacted to advocate for sustainable residue management, restoration and conservation of soil in Kenya. The evolution of policies concerning agricultural wastes in Kenya since 2010 is presented in Table 1.

Table 1. *Evolution of policies on agro-wastes since 2010.*

Year	Policy / Strategy / Legal Framework	Focus	References
2010	Constitution of Kenya	Encourages the public to conserve the environment by eliminating activities that endangers the environment by ensuring sustainable management practices	[24]
2013	National Climate Change Action Plan (NCCAP) 2013-2017	Identified that limiting fire in crop lands and other land management systems can reduce emissions by 1.1 and 1.2 MtCO2 e by 2030	[25]
2017	Kenya Climate-Smart Agriculture Strategy (2017-2026)	Promoted sustainable alternatives such as mulching and composting	[12]
2021	Sustainable Waste Management Act (2021)	Encouraged zero waste principle including prevention of burning of wastes by promoting circular economy resulting in wealth creation, employment and pollution reduction.	[26]
2023	Agricultural Soil Management Policy (2023)	Recognized use of agro-wastes as soil amendments discouraged burning.	[27]
2025	Ministry of Environment, Climate Change and Forestry Draft strategic plan 2023-2027	Promote sustainable waste management strategies, pollution control and circular economy	[28]

2. Factors Influencing Open Field Burning of Agro-wastes

A number of factors drive the adoption of this practice. For instance, mechanical harvesters generate large quantities of residues and with limited time between harvesting and next planting period, farmers are forced to burn the residues [29]. Lack of finances to purchase machinery for managing wastes, absence of appropriate management technologies, insufficient storage and transportation facilities, and ignorance of farmers on the effects of burning have also been reported to also contribute to residue burning [30]. Additionally, the belief that burning of crop residues control weeds, pests and disease is another factor contributing to the practice [31].

Expensive no-burn management techniques such as happy seeders, evolution in technology, and dependency on farm implements such as low horsepower tractors have also been linked to crop residue burning in India [32]. Some government policies may hinder farmers to explore alternative techniques for waste management. For instance, the Punjab Preservation of Subsoil Water Act groundwater conservation policy of 2009, specifically delays rice transplantation which shortens the window between the rice harvest and wheat sowing, forcing farmers to resolve to burning to clear the fields [33]. Provision of adequate financial support from the government and awareness creation will encourage farmers to adopt alternative strategies to mitigate environmental, health and social challenges caused by open burning of agricultural wastes [34]. The major drivers of burning are presented in Figure 4.

***Figure 4**. Drivers of crop residue burning [31].*

3. Impacts of Agricultural Residue Burning

3.1. Air Pollution

Agricultural activities, forestry and other unsustainable land use practices are major contributors of global emissions, contributing approximately 22% of global greenhouse emissions as at 2019 [35]. Burning of agro wastes is among major contributors of climate change globally. It is estimated to be the second largest sources of air pollutants from biomass burning, after forest fires, with approximately 2020tg/yr which accounts for about 25% of the global biomass burned [36]. The practice releases CH_4, CO, CO_2, SO_2, NO_x, and PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ into the environment. These pollutants impair the air quality, forms smoke and haze and causes rise in heat waves contributing to global warming [37]. Particulate matter released are defined by the size of the suspended particles in the air. PM_{10} refers to particles less than 10 µm, $PM_{2.5}$ to particles less than 2.5 µm, and $PM_{1.0}$ to very fine particles less than 1 µm [38].

Volatile organic compounds are also released into the atmosphere which undergo series of chemical reactions with Nitrogen oxides to form ground level ozone, which is a secondary greenhouse gas with significant climate change effects [39]. The dispersion of these pollutants is influenced by meteorological factors such as wind direction and speed, temperature and relative humidity which ultimately determine the air quality and associated effects [40]. Nitrogen oxides and Sulphur dioxide released during burning combine with water vapour, oxygen and other chemicals to form nitric acid and sulphuric acids compounds that precipitate inform of rain, fog and snow [41]. Globally, maize residues contribute to the highest amounts of emissions as presented in Figure 5.

In Kenya, it is reported that 67% of total emissions are produced from the agricultural sector and these emissions have significant effects on the climate change [43]. The particulate matter released from the burning of crop residues is estimated to be 17 times higher than that of the emissions from other sources such as motor vehicles, waste incineration, and industrial waste [44]. The dense fog observed during the post-harvest period, combined with smoke from straw burning, results in smog, which creates a dense layer of haze over northern states [45].

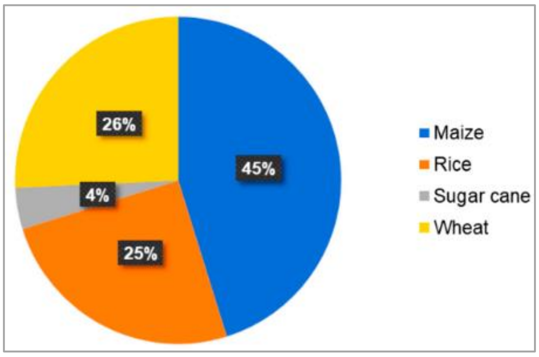

***Figure 5**. Agricultural wastes with leading CO_2 emissions [42].*

Emission of greenhouse gases has reduced the air quality in Nigeria through burning of agricultural waste products. With an estimated population of 218million people as at 2022, increased demand of food resulted in significant generation of agricultural residues [46]. Greenhouse gas emissions increased in increase in Iran over 50 years due to increase in wheat production and reduce in Italy due to reduction in wheat production over the years [47]. Burning of rice straw in Egypt is a major source of greenhouse emissions that has impaired air quality [48]. The statistics estimate that approximately 30 million tonnes of agro-wastes are produced nationally and the type and quality differ between regions [49]. It has been estimated that 11 tons of CO_2-equivalent per ha of land, NO_x and fine dust particles $PM_{2.5}$ are released during autumn seasons which highly affect the quality of air contributing to climate change and endangers public health [50].

3.2. Soil Quality

Burning of crop residues degrades soil quality by depleting organic matter, carbon, nitrogen, phosphorus, potassium, sulphur and bacteria population present in the soil that are responsible for health functioning of soil [44]. During burning, the highest amount of nitrogen is lost (80-90%) followed by sulphur (50%), phosphorus (25%) and potassium (20-25% [51].

During combustion, soil organic matter is broken down to release Potentially Toxic Elements into ashes and smoke which either leach or accumulate into the soil. Additionally, changes in electrical conductivity and pH of soil due to burning influence release of Toxic Elements which increases their mobility and reduce competition on adsorbing sites. Over time, accumulation of these elements in the soil reduces their fertility and ultimately affects plant growth [52]. Moreover, the emissions from burning crop residues causes accumulation of toxic substances like mercury which degrades soil quality and affects water quality [53, 54].

Burning leads to reduction in physical properties of soil making it susceptible to erosion, reduction in stability and water holding capacity by destroys pores. Furthermore, it alters the chemical properties by increasing acidity and destroying micro-organisms that provides nutrients to the soil [51]. Although some studies have suggested that low intensity burning can enhance soil nutrients by releasing organic matter, exposure to fire over a long period leads to nutrient loss through leaching and volatilization, a practice which reduces nutrient cycling and microbial activity which therefore impacting soil fertility and agricultural activity [55].

3.3. Health

Burning of agricultural wastes releases harmful pollutants such as Polycyclic Aromatic Hydrocarbons which contain carcinogenic and mutagenic properties and particulate matter which poses serious threats to the human health. Exposure to even low levels of certain PAHs such as benzo(a)pyrene over long periods has been associated with cancer in laboratory animals [56].

Particulate matter released in air consists of extremely small particles that are widely dispersed into the atmosphere and are able to easily infiltrate the respiratory system posing major risk to human health [39]. Short term effects of these pollutants include eye irritation, vomiting, nausea and diarrhea. Long term exposure has been associated with Deoxyribonucleic Acid mutation decreased immune system, cataracts, kidney and liver damage, asthma and lung abnormalities [57]. People who are more susceptible to being affected are the elderly, children, and people with pre-existing respiratory and cardiovascular conditions. Diseases like asthma, bronchitis, cancer, lung capacity loss, irritation in the eyes, chronic obstructive pulmonary disease, and other disorders become prominent in the affected regions. This in return causes a decrease in mortality rate threating the world's population [58]. Health issues lead to the decrease in working capacity, increase in road accidents during burning seasons due to reduced visibility on the roads. Pollution also affects the health of animals, birds and insects living on earth [39].

It has been reported that exposure to $PM_{2.5}$ which possess high oxidative potential, can lead to cellular oxidative stress which can result in apoptosis and necrosis, potentially leading to lung cancer development over time. The presence of organic chemicals in those fine particles has been linked to an increased cardiovascular risk, particularly through pro-atherogenic effects [59]. Additionally, $PM_{2.5}$ and its constituents such as Black Carbon and Organic Matter are associated with visual impairments from long term exposure [60]. A health impact assessment on the potential of PAH emissions to cause cancer reported that excess lifetime of cancer risk from inhaling the emissions was estimated to be 1.2×10^{-1}, reportedly higher than the acceptable risk limit of 1×10^{-6}. This was attributed to the presence of specific PAH compounds such as Benzo [a] pyrene and Benzo [b] fluoranthene which are known for their carcinogenic properties [61].

3.4. Mortality Rates

A study in North Thailand highlighted that the average life lived years with disability annually as a result of ambient $PM_{2.5}$ per 100,000 population is approximately 41,372 years, and for PM_{10}, it is 59,064 years. Mortality rates from cardiopulmonary diseases and lung cancer from $PM_{2.5}$ were 0.04% and 0.06% of the total population while deaths caused by PM_{10} were approximately 0.06% and 0.08% [62].

Between 1990 and 2015, deaths due to air pollution in South East Asia has increased to 1.2 million. In India, it is estimated that more than 600,000 people die prematurely each year due to exposure to polluted air. The life expectancy of the Delhi inhabitants has decreased by about 6.4 years due to exposure to a high level of pollution [63]. India also reported that 78% of premature deaths is due to burning of agro-wastes which is three times higher than the deaths caused by diseases like malaria and Tuberculosis [39].

In Africa, over 1 million people each year are estimated to die prematurely from exposure to indoor and outdoor air pollution [64]. The mortality rate resulting from open biomass burning is reported to be approximately 106,000 (63%) annually. Premature have been reported to account for 48,000 annually with Central Africa being the most affected region with estimated 30,000 (56%) premature deaths [65, 66]. The community- based initiatives that could prevent residue burning and ultimately prevent health related issues from pollutants exposure include strengthening cooperative societies that can help coordinate knowledge dissemination, more demonstrations and awareness from institutions on effects of burning, provision of monetary benefits to farmers who adopt no-burn strategies and enhancing government communication about sustainable agricultural practices [32].

3.5. Socio- Economic Impact

Burning releases harmful pollutants to the environment, which affects the health of human beings leading to increase in health care costs and decreased productivity. This lowers economic development among the affected communities. Poor visibility also affects traffic which hinders tourism activities [67]. The National Bureau of Economic Research of India reported that the average annual external damages are estimated to be approximately $ 7,600 following the mortality costs caused by burning agricultural residues while the revenues generated from paddy production is approximately $ 500 per acre, which is lower making the mortality cost outweigh the revenue [68].

In Kenya, large amounts of residues are generated after harvesting maize and their utilization have only been limited to livestock feeds and soil enhancement, while the remaining residues are disposed through burning. At the same time, the country is experiencing shortages of raw materials for paper manufacturing due to depletion of forest covers These residues can be explored to produce valuable products for manufacturing pulp and paper [69]. This will provide income to farmers by selling the residue to paper industries and boost the country's economy by reducing importation of paper products.

4. Alternative Management Practices of Agricultural Wastes

Sustainable practices for land restoration and residue management involves utilization of agricultural residues in conservation agriculture among other management techniques such as energy applications. These are key practices in mitigating climate change and ensuring proper management in agricultural systems [70]. Alternative techniques of managing post-harvest agricultural wastes exists and their adoption could significantly reduce unsustainable practices.

4.1. Animal Feeds

Crop residues account for 50% of livestock diet in developing countries. In Western Kenya, farmers practice crop-livestock system. Maize is the main cereal produced in the region and the residues are either ploughed back into the soil to enhance soil health or utilized for livestock feeds [69]. In Trans Nzoia County, 83.5% of the farmers use maize stovers for dairy farming and 5.8% utilize bean straws, millets and sorghum [71]. In Ahero regions, 71.21% of people utilized rice straws as livestock feed during dry season when natural forage such as grass are scarce feed [72]. The International Livestock Research Institute reports that crop residues contribute to significant percentage of livestock feeds, with maize stalks having the highest rank index of 64/80 among other fodders meaning that approximately 80% of the farmers across the USAID-Kenya [73]. Kenya Crops and Dairy Market Systems (KCDMS) counties utilize maize residues as presented in Table 2.

***Table 2**. Agricultural residue rank index for KCDMS counties.*

County	Maize stover	Sweet potato vines	Sugarcane topes	Legume crop residue	Rice straws
Migori	9	5	1		
Kisii	8	3	6		5
Kisumu	4	3			
Bungoma	9	6	6		
Kakamega	8	6	4	3	
Kitui	10	3		3	
Makueni	8			4	
Taita Taveta	8				
Rank Index	64	26	17	10	5

4.2. Composting

Compositing utilizes microbial activity under controlled conditions of heat, moisture and aeration to break down the wastes into organic matter which is then applied as organic fertilizer to provide nutrients to the soil [74]. The nutrients obtained from composting are nitrogen, potassium, and phosphate which act as a good organic fertilizer to the crops.

Composting can be done alone or with combination of livestock residue and the resulting compost can then be collected and added to the soil as organic fertilizer. It is an appealing alternative to stubble burning owing to its ability to turn waste in a farm into valuable product by simply packing crop residues into piles or pits for a long time [44]. The practice is common in countries like India where large quantities of rice and wheat residues are produced. Techniques such as vero-composting, mechanical composting and co-composting are some of the methods used to prepare compost [75]. Compositing is therefore an attractive alternative of managing agricultural residues to provide organic matter in the soil [76].

4.3. Soil Enhancement

Crop residues undergo controlled burning to produce biochar that can be used to enhance soil fertility, stimulate growth of plants and ultimately increase agricultural productivity [77]. Biochar production using agro-wastes is more efficient in developed countries due to established policies and is a promising alternative to mitigating agricultural wastes [78]. Biochar has the ability to improve soil physical, chemical and biological properties through water and nutrients retention, pH improvement, biota activity improvement, and pollution reduction in swamp lands boosting the country's food security [79].

Biochar has a molecular structure that is characterized by high microbial and chemical stability [80]. It enhances soil structure and its ability to retain water due to presence of hydrophilic functional groups with pores allowing water retention. It has alkaline pH, low bulk density, ability to form aggregates and good electrical conductivity [81]. It is enriched with nickel metals which increase root dry weight, height of the plants, and ultimately increase crop yield [82]. A recent study by [83] reported that biochar application improved organic matter content, pH, and nutrients which enhanced the overall productivity and soil health in Northern region of Ghana.

4.4. Carbon Sequestration

Biochar contains stable aromatic carbon that takes long to degrade and does not return to the atmosphere hence reducing the amounts of NO, CH_4 and CO_2 emissions to the atmosphere. Reduction in emissions ultimately reduce climate change [84]. Figure 6 represents carbon sequestration from biomass residue.

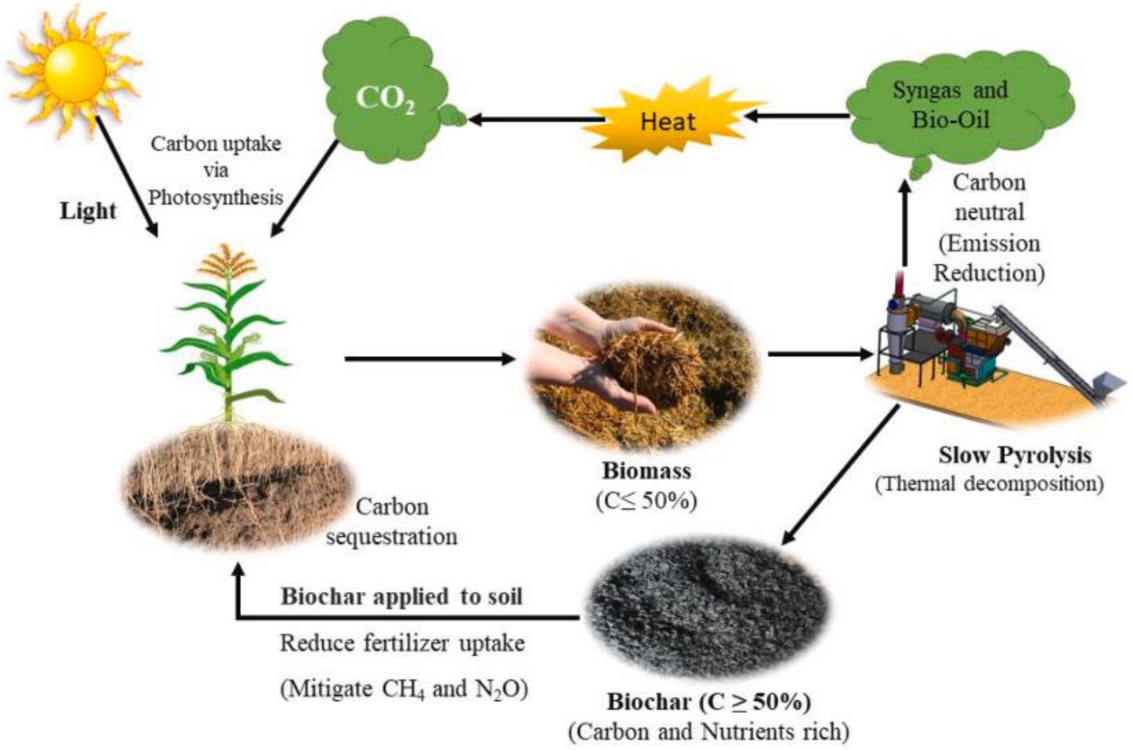

Figure 6. *Carbon sequestration from biochar [81].*

A study reported that biochar use could mitigate 2.23 million MT CO_2 emissions, underscoring its dual benefit for agriculture and climate. The analysis emphasizes the need for strategic investments and policy support to scale biochar adoption effectively [85]. Mitigation of methane and global warming potential on applying chemical fertilizer, biochar derived from rice straw, chemical fertilizer and raw rice straw was analyzed. They displayed significant reduction in net GWP, CO_2, CH_4, and greenhouse gas emission intensity by 39.5%, 37.4%, 42.9%, and 67.8%, respectively [86].

4.5. Construction

It has been estimated that production of 4billion tonnes of cement accounts for 8% global carbon dioxide emissions which needs to be reduced. This has necessitated the use of supplementary materials obtained from agricultural wastes [87].

Agricultural wastes have gained attention as alternatives in the construction industry because of their cost effectiveness, and environmentally friendly nature. They aid in achieving sustainability goals through pollution reduction and other risks [88]. They have been added to concrete to supplement cement and their application has displayed improved structural properties [89]. Other crop residue wastes such as palm fibre and shells, groundnut shell ash, and coconut husk have gained interest as potential pozzolanic materials due to high silica content to replace conventional cementitious materials to meet sustainable development goals and affordable housing programs especially in Africa with housing crisis [89, 90].

Rice husks have been combined with other fibrous agricultural wastes using circular economy model to manufacture a range of furniture products. For instance, a company in Kikuyu town called Funkidz furniture compress and compact these products to create items such as partition boards, and ceiling boards [91]. Bio-corn Products EPZ Limited in Uasin Gishu county utilizes corn cobs, a waste product from maize farming to manufacture chemical products called furfural which is used as a solvent in construction industries. It also generates income through importation to Europe countries and USA [92].

4.6. Pulp and Paper Production

Wood is a hard, fibrous organic product extracted from the xylem of trees. Its continuous exploitation to manufacture pulp and paper poses a threat to environment due to deforestation and emission of greenhouse gases [93]. The need to protect forests and reduce pollution has necessitated research for alternative materials for paper manufacturing. Corn stalk, sugarcane bagasse, rice stubble, wheat straws and cotton stalks poses similar physical and chemical structures to wood fibres and can be promising alternatives to replace wood [94]. In Kenya, wood is the main raw material in paper industries. However, its continued utilization has led to decline of forest cover as only 7.4% of total landmass is covered with forest. Agricultural residues from crops such as maize are produced at the end of harvesting season and can be used as raw materials in paper industries [95].

Maize residues are composed of 20% leaves, 8% husks, 14% cobs, 42% stalks, and 16% other components placing stalks as one of the most spread crop residues worldwide. Corn stalks can be processed using alkaline extraction and soda pulping to produced fibres for paper manufacturing [96]. They contain substantial amounts of glucan, xylan, and arabinan, which are key components for fiber production and fibre with good mechanical properties can be obtained by optimizing extraction conditions [97].

4.7. Composites Development

Agricultural wastes contain lignocellulosic fibres with reinforcing properties that have the ability to embed polymer matrix. They are preferred due to their abundant availability, eco-friendly nature, lightweight, and offer cost effective advantages. [98]. The incorporation of these fibres into polymer composites have been reported to provide sustainability since conventional resources are rapidly depleting, expensive and non-renewable [99]. Plant derived bio-polymers from straws, stalks, leaves and husks such as starch, acetate, chitosan and cellulose are incorporated into bio-composites [100]. Pineapple leaf fibres have been incorporated to thermosetting and thermoplastic matrices to replace synthetic glass fibres [101]. A study to evaluate the suitability of using rice straw pulp to produce bio-composites for acoustic absorbers for industrial noise control reported a better sound absorption capacity than composites made from synthetic binders [102].

4.8. Energy Applications

The global demand for energy is expected to increase with increase in population. Fossil fuels are rapidly depleting due to over utilization and its consumption has significant environmental impacts. It is reported that approximately 21.3 billion tons of CO_2, and other harmful gases are released due to combustion of fossil fuels negatively impacting the environment [103]. As a result of this, clean sources of energy are being exploited to meet the increasing energy demands [104].

Agricultural wastes biomass has been explored as potential sources of briquettes for electricity generation, heating and cooking fuels. Corn stalks, sugarcane bagasse and wheat straws which are usually burned have the potential to be converted into bio-briquettes to provide renewable, affordable and sustainable source of energy [105]. These wastes contain different proportions of hemicellulose, lignin, and lignocellulosic materials that plays an important role in converting them into hydrolysate used in bio-energy production [106].

4.8.1. Biogas

In Kenya, the high volumes of maize produced results in large quantities of maize stalks which are usually disposed by burning, negatively impacting the environment and public health. In Counties like Uasin Gishu, alternative management techniques these residues are necessary. Some studies have reported that maize stalks can be used to generate biogas through anaerobic fermentation [107]. A recent study to investigate potential of maize stalks to produce biogas was conducted in Western part of Kenya. The residue has high methane yield potential and the bio slurry produced as digestate can enhance soil health and reduce the demand for inorganic fertilizers in the region. [108].

4.8.2. Briquettes

Sugarcane bagasse has been reported to have the potential to produce briquettes, a source of fuel that can be used to substitute charcoal fuels. This technique can help reduce indoor air pollution and embrace Kenya's circular economy [109]. It is used by sugar companies as feedstock for heating boilers [110].

4.8.3. Biofuels

Biofuels such as bio-oils, bio-bricks and syngas can be produced from agro wastes without jeopardizing food security. They can be utilized directly as fuel, gaseous fuel, liquid fuel (bio-ethanol) or as pellets [111].

Various processing techniques are utilized to convert agro-wastes to fuel. Biochemical method utilizes microorganisms and enzymes to convert the cellulose and hemicellulose to sugars which undergo fermentation producing ethanol [112]. Pyrolysis method is used to produce biochar and synthetic gas under limited oxygen by transforming long chain molecules into short chain molecules resulting into concentrated fuel oils [113]. Liquefaction converts biomass into bio-oils and biofuels using heat as a catalyst performed under high temperatures (250-370°C) with more moisture [114]. Gasification method converts biomass to gases such as CO and H_2 at even higher temperatures (900-1200°C) [115]. Figure 7 represents the transition from burning method as residue management technique to alternative sustainable techniques.

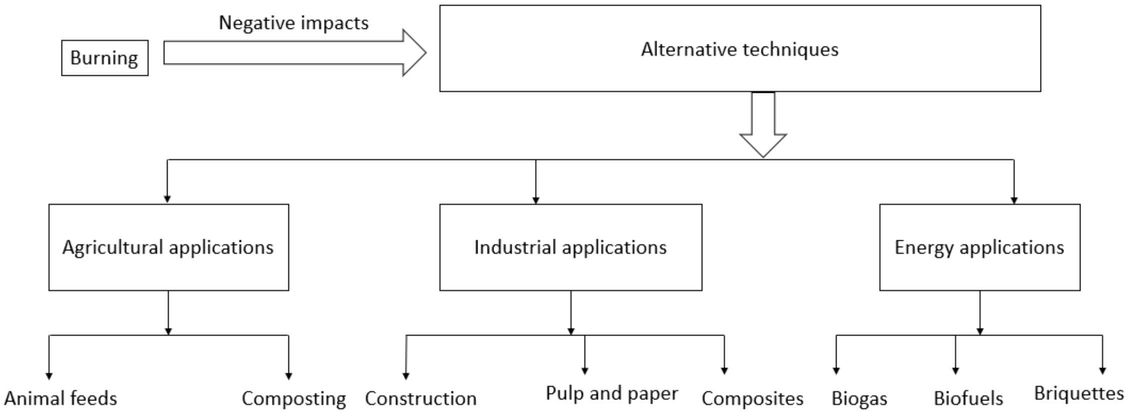

Figure 7*. Transition from burning of crop residues to sustainable alternatives.*

5. Technology Integration in Agriculture

Information, communication and technology tools employ remote sensing technologies, digital imaging, mobile applications, and geographic information systems to efficiently and effectively assess and monitor crop residue cover on agricultural lands. [116].

5.1. Satellites Remote Sensing Methods

Remote sensing tools quantify areas that are burned as a result of fire activities including crop residues. The method involves the application of spatial analysis and mapping techniques in land management and environmental monitoring [117]. Harmonized Landsat Sentinel-2 analyze spectral values from various bands by combining data from Sentinel -2 and Landsat 8 satellites, offering frequent and high-resolution optical observations that capture changes related to harvesting and burning events. [118]. World View 3 and PRISMA satellites provide short-wave infrared reflectance and deliver high-resolution imagery to map crop residues at field or parcel scales with high confidence [116]. Thermasl remote sensors are used for near-real-time monitoring of burning events, and multispectral satellite sensors are utilized for mapping the area that has been burnt [119].

5.2. Geographical Information Systems

GIS captures, stores, analyses and visualizes spatial and geographical data, enabling smart and data-driven decisions in the agriculture sector, enabling farmers to monitor various sectors [120]. QGIS is used for analyzing and process data captured by drones and unoccupied aerial system high-resolution imagery on agricultural fields [121]. ArcGIS isolates agricultural areas and ensures that subsequent analysis is focused solely on relevant cropped lands. It also provides a technique used to group continuous data, into distinct classes which helps in categorizing fields into levels such as bare soil, low cover, moderate cover, and high cover [122].

Google Earth incorporates data from the National Aeronautics and Space Administration and Landsat which leverages cloud computing services to provide analysis capabilities [123]. The tool contains numerous open-access remote sensing datasets and various algorithms which can be easily accessed for different applications, such as producing country-wide cropland inventories [124].

5.3. Mobile Device Applications

Mobile devices are equipped with sensors, digital cameras, and global positioning systems that can monitor real time farming activities and perform crop residue analysis effectively. Apps such as Crop Residue Estimator uses an automated image classification method which requires pixels that represent objects such as crop residues to be selected [125].

6. Conclusions and Future Directions

The paper addressed burning technique to prepare lands for next planting season. The practice emits Greenhouse gases and particulate matter, presenting a significant challenge to the environment, public health, soil biodiversity, productivity and economic development. The practice is mostly driven by financial constraints, policies, insufficient technology among other factors. Sustainable management practices such as converting agro-waste into biochar, compost, development of composite materials, manufacture of pulp and paper, and conversion into clean energy offer sustainable alternatives over open field burning. Crop residues like maize stalks in Kenya is mostly utilized for animal feeds and the rest is disposed through burning, driven by inappropriate management techniques. To encourage full adoption of alternative practices, strict policies such as anti-burning regulations should be enacted. Capacity building and awareness on sustainable practices should be done through county extension services. Subsidizing machineries that enable easy collection and processing of agro-wastes should also be done. Additionally, the government should fund institution-based innovation hubs for agro wastes processing and material testing and link residue producers to industries. Finally, monitoring and evaluation tools like remote sensing, Geographical Information Systems and mobile extension services should be utilized to enable real-time monitoring of agricultural activities. Embracing these practices is a necessity to reducing burning which ultimately drive climate action, foster economic growth, raise a healthy generation free of pollutants and boost agricultural productivity in Kenya and at global level.

Abbreviations

MT	Metric Tonnes
SO_2	Sulphur Dioxide
CH_4	Methane
CO_2	Carbon Dioxide
NOx	Nitrogen Oxide
CO	Carbon Monoxide
PM	Particulate Matter
PAH	Polycyclic Aromatic Hydrocarbons
GIS	Geographical Information Systems
GWP	Global Warming Potential

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Conflicts of Interest

The authors declare no conflicts of interest.

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