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Review

A Review of Systems Thinking Perspectives on Sustainability in Bioresource Waste Management and Circular Economy

Shivangi Jha [1,2], Sonil Nanda [3], Oscar Zapata [2], Bishnu Acharya [1] and Ajay K. Dalai [1,*]

1 Department of Chemical and Biological Engineering, University of Saskatchewan, Saskatoon, SK S7N 5A9, Canada; shx190@mail.usask.ca (S.J.); bishnu.acharya@usask.ca (B.A.)
2 School of Environment and Sustainability, University of Saskatchewan, Saskatoon, SK S7N 5C8, Canada; oscar.zapata@usask.ca
3 Department of Engineering, Faculty of Agriculture, Dalhousie University, Truro, NS B2N 5E3, Canada; sonil.nanda@dal.ca
* Correspondence: ajay.dalai@usask.ca

Abstract: A plethora of sustainability-related challenges plague the modern world, among which is residue management. The significant implications of waste management on local populations and the global climate system have propelled research efforts toward residue management. Improved understanding and predictions in biomass residue management can help identify opportunities to advance residue management to address these complex challenges. In recent years, sustainability science has gained momentum and is viewed as the most effective approach to addressing wicked problems. For instance, the release of greenhouse gases into the atmosphere is a major contributor to climate change. This review examines how a greater knowledge of human–environment interaction and the value of ecological services could facilitate the recycling of agricultural and forestry wastes for their uses in bioenergy production and soil protection. In addition, it highlights the connection between biomass residual management and the United Nations Sustainable Development Goals, thereby strengthening the circular and ecological economy. Additionally, this review also discusses how interdisciplinary and systems thinking can contribute to the advancement of biomass residue management. This review aims to explore how the principles of sustainability science and systems thinking can help enhance the reutilization of agricultural and forest residues through biomass residue management. It also aims to assess their potential in reducing environmental and social impacts.

Keywords: circular economy; greenhouse gas emissions; sustainability science; systems thinking; waste management; United Nations Sustainable Development Goals

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1. Introduction

The growing feeling and awareness that the environment and society are interrelated entities that need to be examined and handled appropriately gave rise to the concept of sustainability. There are various interpretations of the sustainability concept, depending on the prioritization of the various academic disciplines. The ability to meet current social, economic, and environmental requirements without compromising the needs of future generations has previously been described as "sustainability". Alternative interpretations of sustainability have focused on maintaining the world in a healthy, resilient, and adaptable state that promotes the flourishing of all species [1]. It should be noted that the concept of sustainability is continually evolving. Sustainability science is the study of the interconnections between environmental and societal systems and how they affect environmental issues such as climate modeling and water chemistry [2]. Bettencourt and Kaur [3] defined sustainability science as a fast-growing interdisciplinary field that utilizes engineering and policy perspectives to manage human, ecological, and socio-economic systems. The field of sustainability science has a worldwide reach and is predicted to have a substantial impact. Its expansion has resulted in new prospects for scientific cooperation and collaboration.

In recent years, sustainability science has gained momentum and is viewed as the most effective approach to addressing wicked problems. Wicked problems are unidentifiable problems that cannot be solved through straightforward solutions. Additionally, wicked problems are exacerbated by being manipulated by and collaborating with systems other than natural systems, such as the social and political domains. Solving such complicated problems requires an in-depth understanding of the stakeholders involved and an innovative design-thinking solution-based approach. Science acknowledges that unraveling the causes and impacts of wicked problems is challenging, and addressing wickedness requires integrating multidisciplinary knowledge and value-laden potential solutions judgments. Despite the alignment in how social science and natural science understand wicked problems, there exists a tension between the two sciences [4]. Social science and systems thinking aim at understanding the knowledge that is contextually framed with limited references to natural science, while natural science emphasizes natural portrayal but with limited or no focus on the social aspects such as power and justice. However, the overall nature of sustainability and related problems related to it are best understood through multiple sciences and perspectives, thus calling for the inclusion of both the perspectives of social science and natural science. Through the lens of systems thinking, sustainability problems can be identified as wicked problems, a combination of robust issues that can only be understood after finding solutions to them [5]. The main controversy is whether actual solutions can be reached when the problem itself is unknown or whether the problems are better alleviated, considering that they are continuously embedded with long-term impacts. The greatest challenge in addressing wicked problems is that solutions may not be transferable due to the variation of contextual specificity of each problem, which establishes a combination limitation feature [5]. Additionally, the complexity of the wicked problems is evident in the super-wicked problem's existence, as is the case with climate change, which is a key concept in this review.

Based on multiple research findings, addressing climate change is a complex undertaking of the factors that offer solutions and problem interchanges [6]. However, as discussed in this article, wicked problems are better addressed through the cooperation and integration of practitioners and scholars from diverse disciplines who are engaged in systems thinking to develop a solution-oriented discussion leading toward sustainability. In the case of climate change, as proposed in this review, interdisciplinary discussions could focus on promoting the effective management of biomass residues. This approach has proven to be effective in reducing greenhouse gas emissions and thus helping to address the issue of climate change.

The global production of biomass and waste residue from the agriculture and forestry sectors and municipalities poses an increasing environmental concern due to pollution [7,8]. Due to the increasing efforts to attain sustainability, the interest in utilizing biomass residues is growing [9,10]. The goal is to add value to this residual biomass by reducing its volume to ensure its complete utilization and bringing into focus the concept of biomass residue management. Waste management and valorization is the process of utilizing and handling leftovers from organic matter or organic materials to produce clean value-added fuels, chemicals, and materials [11]. The main objective of managing organic residues is to reduce their negative effects on the environment by optimizing their use, minimizing their production, and promoting sustainability. Among the commonly used strategies for waste management include gasification and anaerobic digestion (to produce gaseous fuels), pyrolysis and liquefaction (to produce liquid fuels), carbonization and torrefaction (to produce solid fuels), and composting (to produce biofertilizers) [12].

When the organic residues are burnt, they release greenhouse gases such as CO, NO_x, and SO_x into the atmosphere, which, in turn, change weather patterns and temperature shifts [13]. These changes are key attributes of climate change. Therefore, the poor disposal of biomass residues through burning contributes to climate change, a natural disaster the world is currently struggling to handle. These changes happened in response to natural processes, such as shifts in the solar system, as well as human activities. Since the Industrial

Revolution, human activities, such as the burning of crude oil, natural gas, and coal, have been viewed as the primary causes of climate change. Climate change is contributing to changes such as an increase in sea levels, extreme weather conditions, and rising temperatures, exposing society and the environment to physical and mental health disorders, land degradation, floods, drought, and storms. Therefore, considering the connectedness of the problems with the community and economic aspects, this discussion will be framed across the four main pillars of sustainability science, which are environmental, human, social, and economic.

There is a close link between climate change and biomass residue management. First, organic residues, or biomass residues, significantly contribute to climate change, especially when poorly disposed. For instance, burning plant residues releases greenhouse gases, which are one of the contributing factors to climate change. The gases absorb heat from the sun radiating from the surface of the Earth, trapping it into the atmosphere and preventing it from escaping space. Hence, the greenhouse effect maintains the Earth's temperature as high, which, over time, changes weather patterns. Second, there is evidence that biomass residue management can be a solution to address climate change [14]. Biomass residue management promotes carbon sequestration and reduces methane emissions. Through carbon sequestration, biomass residue management reduces the amount of carbon released from decomposing or burnt organic matter into the atmosphere [15]. Similarly, decomposed biomass residues produce a substantial level of CH_4, which is a twenty times more potent greenhouse gas than CO_2 [16]. Therefore, through proper biomass residue management, CH_4 emission can be reduced, and consequently, less heat will be trapped, thus helping address climate change. Considering the interrelationship between biomass residue management and climate change, the purpose of this review is to investigate how the characteristics of sustainability science might aid in the improved reuse of agricultural and forest residues through the management of biomass residue needs, and it is a potential advantage in reducing the environmental and social burden.

It is important to recognize that systems thinking can play a vital role in managing waste residues and promoting a circular economy. This approach offers a holistic perspective to enable understanding and address the complex interconnections within these systems. By employing systems thinking, the entire biomass supply chain can be analyzed from biomass production to waste management, thus ensuring that all components and their interactions are considered. Understanding the flow of materials and energy in a resource recovery facility or biorefinery can help identify opportunities to optimize resource use, reduce waste, and improve byproduct management through systems thinking. This approach promotes sustainable practices by integrating environmental, economic, and social factors, ensuring that waste management contributes to the long-term sustainability goals. Systems thinking promotes the integration of innovative technologies and practices helping to create circular economy models that link different sectors, such as agriculture, forestry, municipalities, and heat/power generation. By using systems thinking, stakeholders can more effectively address the complexities of waste management and contribute to a more sustainable and circular economy.

Although there are several benefits associated with systems thinking, there is a scarcity of studies that have connected it to waste management and sustainability goals. This review aims to address the gap by exploring ways to enhance the reuse of waste biomass, particularly agricultural and forestry residues, through the application of sustainability science principles and systems thinking. This approach aims to replace the common practice of burning these materials, which contributes to greenhouse gas emissions and air pollution. The reuse of biomass has been extensively studied through established and emerging technologies, including anaerobic digestion, fermentation, pyrolysis, gasification, and liquefaction. These biorefinery processes are used to produce biofuels, biochemicals, and biomaterials from waste biomass. To our knowledge, this review is the first to connect systems thinking and sustainability science with bioresource waste management and the circular economy, specifically addressing the United Nations Sustainable Development

Goals (UN SDGs). The methodology used to prepare this review involved conducting a comprehensive search of the existing literature in the form of original research, review articles, book chapters, patents, and industry reports accessed through scholarly databases and public domain sources. The literature review focused on collecting articles and reports published mostly within the last 5 to 10 years, ensuring the inclusion of the latest research developments and statistical data. The collected literature was then categorized based on themes, methodologies, and findings. This was followed by a critical analysis and interpretation drawn from the authors' perspectives and insights on systems thinking.

2. Biomass Residue Management

Based on the evidence, one of the most effective approaches for addressing climate change is related to its major pivotal factor, greenhouse gas emissions [17]. Greenhouse gases absorb and diffuse radiant energy, spawning the warming effect. The gases that are mainly responsible for global warming are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), hydrofluorocarbons (HFCs), and hydrochlorofluorocarbons (HCFCs). These gases trap heat in the atmosphere, affecting the Earth's radiative balance and ultimately altering weather and climate patterns on the regional and global scales. Burning fossil fuels in the transportation sectors and for heat and power generation contributes to more than 75% of global greenhouse gas emissions [18]. Fossil fuels and oil are commonly made from animal and plant residues that perished millions of years ago and decomposed below the Earth's surface.

To promote a circular economy, environmentalists are campaigning for the recycling of organic waste to produce more valuable products such as electricity and heat generation. There is also increasing awareness toward practicing conservative agriculture by crop residues to improve crop production and soil productivity. Residual biomass is a good source of nutrients required by succeeding crops and can be relied on to improve the air, water, and soil quality. The development of biomass residue management greatly depends on the understanding of the key reasons why some farmers decide to use burning as the main approach to disposing of residues from crops [19]. The main reason is that, due to the limited time between seasons, farmers have limited time to complete tillage, and this can cause delays in the seeding process, which may negatively affect the next succeeding season's crop. Therefore, most choose to burn as the fastest option for managing the residues, with minimal to no concern about the impact they cause on the climate. Despite the evidence that burning biomass residues contributes to greenhouse gases, few farmers are conscious of this effect. Most studies and climate change awareness messages focus on oil, gas, and coal as the major contributors to climate change, and thus, few farmers understand the impact they cause on the environment by burning activities [19,20].

Most of the literature on reducing greenhouse gas emissions is focused on reducing the global dependence on fossil fuel use such as coal, oil, natural gas, and nuclear energy. Scholars have overlooked the contribution of poor forestry and agricultural residue management practices to greenhouse gas emissions, and this presents a barrier to adequately addressing climate change. There is evidence that poor forestry and agricultural techniques contribute between 19% and 27% of the total greenhouse gas emissions [21]. Burning agricultural and forest residues alone contributes over 20% of the total greenhouse gas emissions, thus contributing to climate change [22]. Environmental sustainability reveals the possibility of maintaining an ecological balance in the Earth's natural environment and conserving natural resources to benefit the well-being of ecosystems [23]. In most developing countries, as a common practice, farmers use agricultural burning to clear and prepare the land and to enhance soil nutrients before planting. However, despite the evidence of how burning agriculture and forestry residues contribute to greenhouse gas emissions, there is a lack of adequate literature on reliable approaches to prevent or reduce the emission of toxic gases from organic materials into the atmosphere while still enhancing the maximum use of the residues.

This paper reviews the human–environment interaction related to the principles of sustainability and UN SDGs based on the four pillars of sustainability. The importance of residue management in the circular economy is related to the economic pillar of sustainable growth to assess and rationalize the role of the four pillars of sustainability science in promoting the reuse of agricultural and forest residues to reduce greenhouse gas emissions and address climate change problems. In the human–environment interaction section, this review article covers concepts such as ecological services to examine the interdependence and interconnectedness between humans and the environment and how these links, in relation, could motivate more people to reuse organic residue, rather than burning them, to conserve, preserve, and protect the environment and the climate. In the circular economy, this article focuses on the economic, social, and human pillars of sustainability science to rationalize the relationship between biomass residue management and circular economy, a model perceived to be primarily important to attain sustainability. Additionally, this article describes how biomass residue management is in alignment with UN SDGs to lead the world toward a sustainable environment, health, and development. Lastly, this article explores the role of interdisciplinary collaborations and systems thinking in promoting biomass residue management and thus mitigating climate change.

To evaluate and rationalize the effectiveness of reusing agricultural and forest residues to reduce greenhouse gas emissions and address climate change, this paper critically analyzes evidence on human–environment interactions, UN SDGs, the circular economy, and interdisciplinary approaches. Based on the results, it is possible to dramatically reduce greenhouse gases and combat climate change by reusing agricultural and forestry waste for things like bioenergy, soil preservation, and animal feeds.

A few knowledge gaps exist in the understanding and adoption of sustainability science in waste management and circular economy, a few of which are discussed here. There is a paucity of literature discussing the synergistic trade-offs between biodiversity and the benefits that humans gain from nature and how ignoring the values of the ecosystem services provided by nature creates a sense of disconnection between humans and the environment, resulting in suffering for both. Consequently, it is essential to appreciate nature and maintain a sense of connectedness. There is a dearth of literature on the topic of residue management's compatibility with UN SDGs and sustainability science elements like long-term thinking from sustainability science. Hence, this review seeks to answer the question of how biomass residue management promotes the UN SDGs and sustainability science elements. The role of circular economy, ecological economy, and bioeconomy in supporting residue management has received little attention. What are the roles of circular economy, ecological economy, and bioeconomy in supporting residue management, and how does the management enhance such economies? Many factors have direct and indirect effects on sustainability science and residual management practice.

3. Principal Elements of Sustainability Science

The effect of burning biomass residue and its cascading contribution to greenhouse gases and climate change can be analyzed through the different key principles of sustainability science. It focuses mainly on addressing complex economic, social, and environmental challenges through the promotion of sustainable development, achievable through the integration of knowledge from diverse fields, such as social science, humanities, and natural science [24]. Therefore, the first principle of sustainability science, also relevant in this article, is interdisciplinary. Sustainability science acknowledges that the economic, social, and environmental systems are interconnected, and thus, the integration of knowledge from diverse fields is critical to solving complex sustainability issues [25]. Interdisciplinary collaboration is key to handling climate change through effective biomass management. Another important principle of sustainability science relevant to this paper is systems thinking, which uses holistic strategies to understand sustainability issues, considering interconnectedness and the association between natural, economic, and social systems [26].

Sustainability science aims at finding a long-term solution to complex economic, environmental, and social challenges. Concerning climate change, human–environmental interconnectedness and human dependence on ecological services are long-lived, and hence, a need for a long-term solution to climate change is a threat to the relationship. Biomass residue management is considered in this paper as an appropriate solution for climate change, since it aligns with the long-term perspective, a key principle of sustainability. The practice is considered in relation to future generations' needs and is critical in enhancing intergenerational equity. Other different key factors governing sustainability science and used in this article are summarized under human–environment interaction, UN SDGs, and circular economy. Together, these key points provide a perspective on sustainability, reflect on the highly effective management of biomass residue, and provoke further thought and discussion, attracting the attention of interdisciplinary teams and systems thinkers.

3.1. Human–Environment Interactions

Human–environment interactions refer to the connection between the environment and society [27]. The interaction can affect human well-being and life, since humans depend on the environment daily [28]. From a social perspective, human–environment interaction is based on central ideas, which include how humans adapt, modify, and depend on the environment [27]. Social systems, environment, and the ecosystem are the three main areas where humans and the environment interact [29]. In human social systems, human and environmental interaction occurs when humans come into direct or indirect contact with the environment. This type of society greatly influences human behaviors and attitudes toward nature, thus impacting ecosystems [29]. Important social attributes include social organization, wealth, knowledge, education, technology, values, and population size. Importantly, values and knowledge influence individuals' perspectives, consequently defining their actions. The degree to which humans will modify ecosystem services is also influenced by factors such as technology, population size, and the knowledge of ecosystem services (Figure 1).

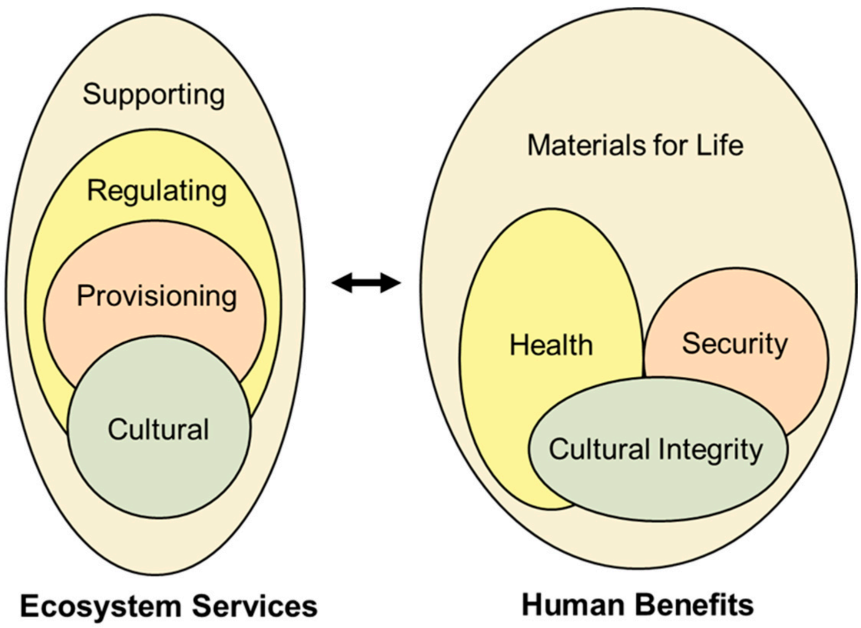

Figure 1. Interactions between ecosystem services and human benefits.

Ecosystem services are defined as the varied benefits that healthy ecosystems and the natural environment offer humans. Healthy ecosystems include grassland ecosystems, aquatic ecosystems, and forest ecosystems. Human society depends on the environment for a variety of benefits, such as natural resources, climate regulation, cultural values, and economic activities. All these benefits are different types of ecological services. Human society, as used in the context of human–environment interactions, refers to a group of people with a shared common organization and lifestyle. In terms of ecological services, the first is supporting services. The environment is the source of supporting services, often overlooked or undermined. Through basic processes such as nutrient cycling, the water cycle, the creation of soil, and photosynthesis, the Earth can support life and ecosystems. In the absence of support services, regulating, cultural, and provisional services would be nonexistent. The second type of ecosystem service is regulating services, and in this, the environment is viewed as a source of services that support human life. For instance, trees filter water and clean the air, tree roots help prevent soil erosion, animals such as bees pollinate flowers, and bacteria are actively involved in decomposition. Regulating systems make the ecosystem functional, resilient, clean, and sustainable through services such as decomposition, water purification, climate regulation, carbon storage, floods, and erosion control.

Third, provisioning service entails the direct benefits humans can extract from nature, including as a source of food, timber, natural gas, plants, drinking water, and medicine. Lastly, as humans interact and modify nature, the changes in nature also cause humans to change, and thus, cultural service is another type of ecosystem service. Nature guides human cultures, societies, and intellectual development, since it is a force constantly in human lives. As early as the ancient civilizations, the ecosystem has immensely influenced the human mind, evident in the drawings of plants, weather patterns, and animals on stones and walls. Cultural services from nature contribute to the emergence and enhancement of culture and substantially impact how ideas spread, creativity, recreation, and knowledge building. Humans can care for the environment in their pursuit of supporting and cultural services through practices such as promoting sustainable land use, reserving the culture of responsible organic residue disposal, supporting the natural process of restoration, and promoting local practices and knowledge, which leads to environmental conservation and preservation.

Despite the benefits humans derive from the environment, humans are quickly losing touch with the environment. Instead of conserving nature to continue benefiting from its ecological services, humans have turned into a threat to nature. We see ourselves as largely disconnected from nature, and thus, we are the leading force contributing to water, air, and land pollution. Increased feelings of interconnectedness and bonding with nature can motivate humans, a key pillar of sustainability science, to promote social awareness and environmental preservation.

Through the lenses of biomass residue management, human–environment interactions are a crucial aspect, because they influence the quality and quantity of available biomass residue, and the impacts caused on the environment in their production, utilization, and reutilization. Biomass residues from forestry and agricultural waste result from human activities and interactions with the environment. Such activities include farming, weeding, deforestation, and harvesting. The quality and quantity of the available residues are reliant on factors such as land use practices, climate conditions, and type of activity [30]. Based on provisional services, a type of ecological service, humans depend on the environment for food. We grow plants and use some of their parts, such as fruits, leaves, stems, or roots, for food. Through environmental awareness and increased human–environment interconnectedness, it can be better realized that burning such agricultural residues contributes to greenhouse gas emissions, which, in turn, causes climate change, thus influencing and regulating ecological services. With such knowledge and motivation for the need to preserve nature, more farmers will be motivated to choose better ways of disposing of and using the residues from their agricultural activities and using organic materials from agricultural activities and forestry maximally.

Through an increased interconnectedness with nature, more humans will be willing to learn and practice sustainable practices that help preserve the environment, such as biomass residue management strategies. Burning biomass residue contributes to the emission of greenhouse gases and climate change. Additionally, burning the residues inhibits soil microorganisms, which are essential in wetlands, grasslands, forests, and agricultural ecosystems. Biomass residue management helps prevent such consequences and sustain human–environment interactions and ecosystem services. Awareness of how humans depend on the environment and the consequences of practicing unsustainable biomass residue disposal could promote biomass residue management strategies. Such strategies include using biomass to generate bioenergy, animal fodder and bedding, board and paper production, and organic manure and materials for mulching and preventing soil erosion.

Additionally, through increased human–environment interconnectedness, regulations and policies to promote the reuse of agricultural and forest residues will be established and enacted. National governments and international institutions can offer incentives to promote biomass residue management while implementing policies and regulations to ensure that agricultural and forestry residues are properly managed in an environmentally responsible manner to conserve the environment and preserve ecological services. Additionally, through increased human–nature interconnectedness, humans could use innovative technologies to promote better ways of managing biomass residues. The technologies can be used in collecting, transporting, and processing the residues in an easier, less costly, and environmentally friendly way. While the reuse of biomass residues is recommended for environment conservation, some practices associated with the management may be a risk to the environment. For instance, farmers may use vehicles powered by fossil fuels to transport biomass residues from the farms to locations where the materials are used for practices such as the production of bioenergy. In such a process, fossil fuel will be used, posing a threat to the environment. However, through proper education, awareness, and use of environmentally friendly transportation options, the biomass residue management practice will be of greatest benefit to the environment.

Based on the evidence, human–environment interaction is an essential consideration when thinking about biomass residue management. For instance, biomass residues arise from human activities such as forestry and agriculture, and how they are managed significantly impacts the environment. Additionally, how well people manage biomass residues significantly depends on human factors, such as the level of knowledge and awareness, access to resources critical for residue management practice, and the commitment to use biomass residue management practices rather than other easier and faster options, such as burning organic materials [31]. Therefore, efforts to promote biomass residue management must emphasize improving human–nature interaction and interconnectedness through increasing awareness of environmental factors and other benefits of conserving the environment, the economy, and social and environmental systems.

3.2. United Nations Sustainable Development Goals for Waste Management

The United Nations has launched the Sustainable Development Goals or Global Goals to end poverty, safeguard the environment, and ensure peace and prosperity by 2030. Actions toward one of the 17 Sustainable Development Goals (SDGs) can affect others. Sustainability requires social, economic, and environmental balance. The member states of the United Nations adopted the 2030 Agenda for Sustainable Development in 2015, which has seventeen interrelated goals and 169 targets. Global development requires intersectoral effort, system strengthening, and novel approaches [32]. Environmental sustainability and agriculture and forestry residue management support SDG #3 (Good Health and Well-Being), SDG #7 (Affordable and Clean Energy), SDG #12 (Responsible Consumption and Production), and SDG #13 (Climate Action), as depicted in Figure 2.

The combustion of agricultural residues emits a large volume of greenhouse gases, such as CO, CO_2, NO_x, and SO_x, making the air unsafe for animals and humans. Researchers have found a significant amount of propene, ozone, and isoprene precursors, which have high ozone formation potential scores [33,34]. Specifically, the aerosols from burnt biomass residues have been found to interfere with the global carbon cycle, rainfall, atmospheric circulation, air quality, diversity and ecosystem, and vegetation [35]. The impacts caused by the aerosols cause the atmospheric temperature to increase, which, in turn, affects climate. A significant number of mortalities worldwide are reported due to air pollution [36].

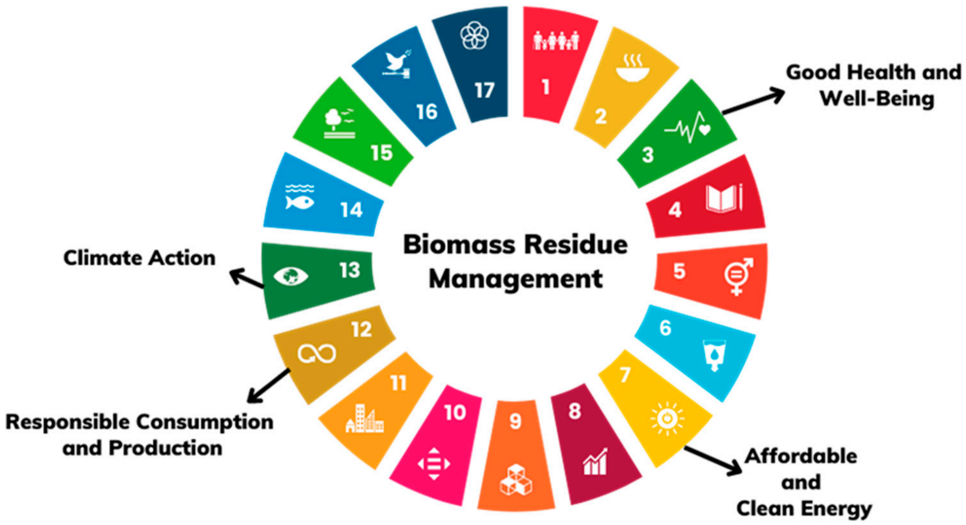

Figure 2. Interrelation between biomass residual management research and UN SDGs. Please refer to the United Nations Sustainable Development Goals for detailed assignments, definitions and objectives of all SDGs.

Several UN SDGs are closely linked with the previously mentioned four ecological services, since the ecosystem is a crucial supporter of sustainable development. For instance, water availability, reduced pollution, and soil fertility are fundamental for food production, which promotes SDG #2 (Zero Hunger) [37]. Additionally, sustainable residue disposal and land management practices such as conservation agriculture and forestry play a major role in maintaining and provisioning ecological services and supporting food security. Besides food security, ecosystem services from the environment, such as water purification and filtration, are essential for ensuring the availability of clean and safe water, which is the central focus of SDG #6 (Clean Water and Sanitation) [38]. Humans can promote ecosystem service and the SDG by protecting water habitats, such as wetlands, to ensure a sustainable supply of quality water. SDG #13 (Climate Action) campaigns for practices that help preserve the environment from any form of threat. Regulating ecological services such as climate regulation and carbon sequestration plays a crucial role in promoting adaptation and mitigating climate change [37]. Human activities such as the responsible disposal of materials containing carbon and other greenhouse gases such as organic residues could help promote the SDG and regulate ecological services.

In the modern world, energy is an essential support to sectors such as businesses, education, medicine, infrastructure, and communication. However, globally, more than 700 million people lack access to a reliable source of electricity [39]. A significant amount of those with access use fossil fuels such as oil and gas, coal, firewood, and charcoal as the major source of energy [29]. Fossil fuels release greenhouse gases into the atmosphere, resulting in impacts that are harmful to the environment and human well-being. Therefore, in response to this issue, the United Nations is focused on enhancing the production of clean energy. Clean energy refers to energy generated through environmentally friendly systems that do not release toxic gases into the atmosphere [40]. SDG #7 (Affordable and Clean Energy) can be viewed as emphasizing an individual's social welfare, financial stability, environmental well-being, or a mixture of these three aspects.

Besides promoting SDG #7 (Clean and Affordable Energy), bioenergy conversion and applications are also related to SDG #1 (Reduce Poverty). In addition to creating job opportunities, people can save more when they have access to affordable energy and must spend less on energy. For SDG #3 (Good Health and Well-Being) and SDG #10 (Reduction of Inequality), besides the increased self-sufficiency of inhabitants of rural areas to produce energy, bioenergy contributes to poverty and inequality by offering an energy source that is not only clean but also cheaper than the ones to which rural people have access. Additionally, improved health attained by avoiding burning organic residues and producing bioenergy also contributes to reduced poverty and inequality, since farmers or rural inhabitants will get sick less often and become more productive and able to work more. Biomass residue management, rather than the combustion of forest and agricultural residues, enhances the UN SDGs by contributing to the reduction of overdependence on unrenewable and unsafe sources of energy.

Biomass residue management also aligns with SDG #12 (Responsible Production and Consumption). Biomass residue management promotes sustainable consumption, resource efficiency, waste utilization, a sustainable supply chain, and a circular economy. Organic residues can be used in the production of biofuel, a type of renewable energy, thus encouraging sustainable consumption patterns through a reduced dependence on fossil fuels, which would promote sustainable consumption [41]. When residues from forestry and agriculture are reduced for environmentally friendly purposes such as the production of clean energy or soil conservation, they are put to maximum use, thus promoting the efficient use of resources. The relationship between biomass residue management and SDG #12, through the perspective of the supply chain, reflects the economic benefits of organic residue management [42]. From this perspective, biomass residue management promotes responsible and sustainable production, essential to sustaining supply chains, which, in turn, balances the demand and supply of essential products.

SDG #13 (Climate Action) and its relationship with biomass residue management also relates to reduced poverty and inequality and improved health by mitigating the impacts of climate change. Using biomass for energy improves resource utilization efficiency, enables effective environment waste management, and reduces the dependence on fossil fuels, thus limiting their extraction [43]. Additionally, through effective biomass residue management, characterized by sustainable production, collection, storage, and processing, the environment is saved from adverse impacts [44]. Due to its close link with SDG #13, biomass residue management can be integrated into national and regional climate change approaches, which balances the need for land management and better biomass options while still supporting climate benefits. Currently, most forest biomass comes from forests essentially established to manage the production and supply of pulp and saw logs. Most of these forests also help safeguard the provision of ecosystem services such as the conservation of biodiversity, soil stabilization, and water purification [44]. In these forests, stems that meet requirements are used in the production of sustainable carbon storage materials such as wood panels and lumber, and the residue is used as a source of bioenergy.

The impact of biomass residue management indirectly serves several other SDGs. For instance, residue management facilitates control of the volume of toxic gases such as nitrogen oxide and sulfur oxide in the atmosphere. These two gases are mainly responsible for the formation of acid rain, which threatens life on land and life below water. The protection of aquatic and terrestrial habitats and ecosystems is highlighted in SDG #14 (Life Below Water) and SDG #15 (Life on Land), respectively. Thus, residue management remains fundamental for life protection. Several nations and communities rely heavily on fishing as a source of domestic food and income. For instance, at least 10% of the agricultural share is accounted for by fisheries [45]. Additionally, the agriculture sector contributes to a significant percentage of multiple countries' gross domestic product value. Economic growth is a component of SDG #8 (Decent Work and Economic Growth). The indirect links between biomass residue management reflect the numerous benefits of environmentally friendly practices.

To attain sustainability, since human dependence on ecological services is interminable, we need to adopt long-term thinking from the view of sustainability. Long-term thinking, as it relates to sustainability science, entails having a lengthy or perpetual perspective or views when developing strategies for sustainability [46]. That means developing and adopting strategies which positive impacts on the environment are long-lived and can be maintained to sustain their benefits to environmental preservation and conservation. Arguably, the UN SDGs that relate to the environment are long-term thoughts that, when effectively implemented, can result in comprehensive and abiding benefits to the environment, offering long-lived solutions to climate change. Concerning biomass residue management, the practice qualifies to be categorized as a long-term thought because it offers a long-lived solution to limiting greenhouse gas emissions and climate change. Additionally, due to the benefits accrued from the practice, biomass residue management is sustainable and thus can be relied on for long-term environment conservation and preservation [44].

The growing biomass market can help improve forest management strategies such as thinning and promoting growth rates, which, in turn, contributes to carbon concentration and reduced loss of biodiversity [47]. On the other hand, the growth in bioenergy could lead to the increased demand and production of energy crops such as hybrid poplars, *Miscanthus*, and willow [48]. An energy crop is a plant grown for use in the generation of energy or the production of fuels and which typically does not compete with sunlight, arable land, soil nutrients, and fertilizers [49,50]. Some of these plants can help in filtering wastewater and restoring degraded land, which are targets in SDG #6 (Clean Water and Sanitation) and SDG #15 (Life on Land), with the ultimate benefit of producing bioenergy. Therefore, based on evidence, the adoption and reuse of agricultural and forest residues through biomass residue management advance SDGs, contributing to the world's transformation through the reduction of poverty, protection of the environment, and promotion of prosperity and good health. Lastly, the translation of knowledge from academic or research labs to societies and communities is not possible without the involvement of industries. Industries play a critical role in scaling up technologies and facilitating the commercialization of products to largely benefit societies. Hence, sustainability science concerning residue management and circular economy also supports SDG #9 (Industry Innovation and Infrastructure).

3.3. Circular Economy

A circular economy is a system based on the regeneration and reuse of products or materials to continue a production system that is environmentally friendly and sustainable [51]. The system is an alternative to linear economy, which is practically an extract—produce—use dump system. The circular economy is a cyclical flow model that emphasizes the recycling of materials and products [52]. Since the beginning of industrialization, the idea of recycling has been common among scholars and experts, accompanied by the notion that recycling helps reduce negative impacts on the environment and stimulates the emergence of new businesses and opportunities [53]. However, for the longest time, linear economy has dominated industrialization development, and the result has been serious harm to the environment [54]. Circular economy, unlike conventional approaches to recycling, emphasizes components, material, and product reuse; repair; cascading; refurbishment; upgrading; and remanufacturing, as well as wind, solar, waste, and biomass-derived energy use throughout the lifecycle of the product [51]. Largely, the concept and practice of a circular environment have been established and developed by professionals such as business consultants, business foundations, business foundations, and policymakers.

Although the scientific research on circular economy is significantly unexplored, ecological economics is an important source of guidance and support for the new policy, business, and practical-oriented ideas of circular economy [55]. The link between ecological economy and recycling and other concepts related to circular economy dates several years back, especially at the macroeconomic level [52]. Concerning sustainability science, ecological economics is a field defined by a combination of challenges and problems related to the governing of economy-related activities in an approach that promotes sustainability, justice, and well-being. The field is more concerned about the relationship between the environment and the economy, with the key assumption that economic activities are reliant on natural resources and systems and that humans are ultimately connected to the health of the environment [56]. Therefore, an ecological economy, akin to circular economy promotes equity, reliance, and sustainability in economic systems, challenging economic models that are centered on profit and growth while ignoring social and environmental concerns [57]. Through ecological and circular economy, a holistic economic development approach, which considers the need to safeguard the environment and the limitation of natural resources, is achieved.

In practice, the circular economy promotes the reuse of resources and materials, which is also viewed as a central and important practice to achieve sustainability in the bioeconomy [58]. Another important link between bioeconomy and circular economy is that the former helps address the issue of the limitation of natural resources, since it promotes the use of renewable and reusable resources in the production of goods and services. Therefore, to achieve sustainability in a circular economy, the use and reuse of renewable resources are encouraged, and thus, the concepts of circular economy, ecological economy, and bioeconomy promote the use of biomass. Although a significant proportion of energy used in the modern world is derived from non-renewable sources such as fossil fuels, biomass is arguably the oldest source of energy by humans [58]. However, the overall use of biomass energy does not ascertain environment conservation, but proper biomass management could help promote sustainability and conservation.

Effective sustainability must be founded on economic and social pillars [59]. The creation of environmentally friendly, socially responsible, and economically affordable models is the basis by which a true circular bioeconomy can be achieved. The concept of circular bioeconomy encourages the sustainable and responsible use of biomass and biomass residue pillars [59]. Biomass residue was conventionally used largely as animal feed, but with the growing demand for clean energy, waste from agriculture and forestry is expected to play a major role in addressing the demand. When the residues are used in fuel production, they become an alternative to conventional disposal approaches such as on-site burning, which has a severe impact on the environment [60,61]. The recovery of biomass waste facilitates the completion of the biomass supply chain cycle.

Unlike the approach of growing energy crops for bioenergy production, the reuse of biomass residues is more sustainable and beneficial when viewed from multiple points [62]. For instance, in the wood industry, only between 50% and 60% of the harvested volume is used, and the remaining proportion goes to waste [63]. An equally significant proportion is wasted in agriculture. However, in a circular economy that promotes bioenergy, waste can be used to produce energy, and this limits the need for growing energy plants, thus reducing the overall cost of biomass production and handling for energy production [63]. Additionally, land space is saved, since there will be no need to grow different plants for wood and food production and others for biomass energy production. The space can be used for other purposes that enhance environmental conservation and the protection of ecosystems. Integrating human growth with natural systems in a way that maintains, nurtures, and improves both is essential to the concept of regenerative sustainability.

As an exemplary case study, in the early 1990s, Sweden cultivated oilseeds, which were used in the production of biodiesel [64]. However, with evidence that growing energy crops was more expensive than using the biomass residues available, the country shifted its focus to wood biomass. Currently, biomass residue accounts for more than one-third of the energy used in Sweden, with wood residue biomass being the largest source of bioenergy [65]. On a global scale, biofuels supplemented 4% of transportation fuels in 2022, equivalent to 2 million barrels of crude oil [66]. Bioethanol and biodiesel are the most commonly and commercially produced biofuels globally. In 2023, the worldwide production of bioethanol and biodiesel was 108 and 48 billion liters/year [66]. Policies that support using biomass residues to produce biofuels exist in more than 80 countries today, although the demand for biofuels is more prevalent in developed countries than in developing countries. The USA, Brazil, Europe, and Indonesia account for 85% of the biofuel demand quenched with the conversion of waste biomass to biofuels. With a notable accelerated production and use of biofuels, Argentina and India increased their biodiesel and bioethanol blending targets, respectively, in 2022. As advanced economies such as the USA, Canada, the European Union, and Japan bolster their transportation policies, the increase in biofuel production is hindered by factors like the growing interest in electric vehicles, enhancements in vehicle efficiency, and high production costs for biofuels.

Biomass residue management promotes regenerative sustainability, because besides the environmental benefits, it is linked to economic and social values. Biomass residue management strives to better the environmental, social, and economic systems for the benefit of current and future generations and so can be seen as an extension of regenerative sustainability. Biomass residual management also illuminates the necessity of learning how to contribute to the environment by tapping the health of ecological systems as a design premise, as opposed to merely minimizing environmental damage. The other perspective of the interdisciplinary approach can help in the integration and study of sustainability science effectively.

4. Interdisciplinary Approaches in Sustainability Science

The concept of interdisciplinary has attracted the attention of scientists from natural and social sciences. The concept demonstrates the integration of ideas, techniques, data, and theories from diverse fields and disciplines. Interdisciplinary approaches combine methods and knowledge derived from different disciplines or fields of study to solve a complex environmental issue that may not be sufficiently addressed by relying on a single discipline. Disciplines such as economics, ecology, engineering, psychology, social science, and environmental science are examples of major fields of knowledge from which experts come and collaborate for common sustainability goals [24]. Through interdisciplinary collaboration, sustainability science brings together experts with diverse knowledge and perspectives in handling environmental and social challenges in an integrated and holistic manner. That entails considering human and natural systems and the relationship between independent systems, such as social, economic, and environmental, concerning the focus issue.

The interdisciplinary approach to the problem leads to systems thinking, which is the understanding of how each pillar of sustainability affects the other. It also entails integrating tools, techniques, and concepts from different disciplines. Additionally, systems thinking leads to an understanding of how various aspects of nature, such as resources, ecosystems, and living beings, depend on each other to form simple and complex relationships to sustain life. The concepts of systems thinking and adaptability play an important role in addressing the knowledge gap and challenges. The idea of how systems thinking can be used in the field of sustainability science and interdisciplinary research approach is a valuable focus.

4.1. Systems Thinking and Analysis

An interdisciplinary approach and systems thinking are both approaches to solving problems [67]. Through systems thinking, the interdisciplinary team views the problem or issue at hand as a section of a larger system [24]. Therefore, the team focuses on understanding each element that makes up the system and how the elements exist and interact with each other to understand the system. In contrast to scientific reductionism philosophy, systems thinking views a problem holistically and seeks to understand it by examining the interaction and linkages between elements. Therefore, viewing sustainability as a system, to better achieve it, an in-depth understanding of the components making up the system and their linkages is required [68]. Such components are the pillars of sustainability: environmental, economic, social, and human. To understand all these pillars and develop a perfect illustration of their relations, a collaboration between experts in various fields related to the pillars is fundamental.

In the modern world of interconnectedness, where humans have developed an awareness of the interconnection between elements in the surroundings, a multidisciplinary approach is being used to prepare learners to adopt systems thinking [69]. A multidisciplinary approach is a curriculum integration strategy that focuses on integrating diverse disciplines and different perspectives to achieve an illustration or understanding of an issue, theme, or topic [70]. Through this approach, one topic is studied through multiple viewpoints or disciplines [69]. Therefore, such an approach can be used to study biomass residue management. The topic can be approached through environmental, social, economic, and health viewpoints. Through a multidisciplinary study of biomass residue management, the environmental, social, economic, and health impacts of the practice are identified and compared to realize the overall advantage or shortfalls, thus informing decision-making [70]. Such a decision can also be achieved by discussing the topic in an interdisciplinary team and viewing the topic through the perspectives of each discipline.

A single-sided view of the reuse of forestry and agricultural residues may not lead to in-depth knowledge [71]. For instance, if the practice is viewed solely from the environmental perspective, environmentalists will likely conclude that biomass residue management helps reduce greenhouse gas emissions and prevent other negative impacts associated with alternative methods, such as burning the residues. However, such a viewpoint may not inform the economic burden or benefit of biomass residue management or the impact of the practice on health. For instance, while biomass residue management is encouraged for its economic and environmental benefits, the practice is linked with air pollution, because the organic matter used can release toxic gases such as NO_x and CO into the air, increasing the prevalence of several cardiovascular and respiratory diseases. Additionally, when the demand and benefits of using agricultural residues for bioenergy production are high, farmers may choose to use a large portion of agricultural and forestry waste on bioenergy production, leaving less organic material to use for animal feed and soil conservation. Therefore, for informed decisions on biomass conservation and reuse, interdisciplinary or multidisciplinary approaches, comprising experts in fields such as environmental conservation, economy, psychology and health, politics, and policymaking, are recommended to ensure that the decisions are founded on systemic knowledge. Through systemic knowledge, the viability of biomass residue management in a specific community, state, or region can be assessed to inform decisions for maximum benefits from the practice.

Systems thinking and analysis can significantly contribute to biomass residue management. First, interdisciplinary research could lead to a deep understanding of the economic, environmental, and social context of biomass residue management [72]. Through a systemic approach, interdisciplinary research could analyze the diverse stakeholders and factors involved in and influencing biomass residue management. Additionally, such research could lead to the identification of potential opportunities and barriers for biomass residue management as a sustainable practice. Second, through research that integrates experts from diverse disciplines, it is easier to identify trade-offs associated with biomass residue management [31]. Interdisciplinary collaborations and systems thinking ensure that an issue is viewed through multiple perspectives in a less biased way to identify both advantages and disadvantages. For instance, the use of biomass residue for bioenergy production could have positive and negative social and environmental impacts. When all the impacts are identified, they can be compared to identify the trade-offs and guide the development of strategies to maximize the benefits while minimizing any negative impacts. Lastly, since interdisciplinary research and systems thinking unite different experts for a common goal, the team can use its diverse skills, knowledge, and experience to develop innovative solutions for improving the effectiveness of biomass residue management [72]. Experts from social, agriculture, and engineering sciences can work together to develop a sustainable, flexible, adaptable, efficient, and inexpensive biomass management residue system, which could be a perfect substitute for burning biomass residues.

Interdisciplinary research and systems thinking can be relied on to advance the broad field of residue management, since experts and knowledge from diverse fields are combined [73]. The combination can lead to innovative, sustainable technologies, policies, and systems for residue management. Additionally, through the collaboration of experts in disciplines such as anthropology, sociology, and economics, the social–economic effects of residue management can be accessed, and strategies for promoting sustainable and inclusive development can be designed. The advancement of any field, including the field of residue management, calls for stakeholders' inclusion. In the context of biomass residue management, stakeholders include policymakers, farmers, local communities, environmentalists, industry stakeholders, and healthcare professionals [73]. These stakeholders can be engaged through an interdisciplinary approach to convey their concerns and perspectives concerning residue management, and their inputs can be used to develop strategies and solutions that align with their preferences and needs. Through engagement and inclusion, all the stakeholders will be motivated to be part of the large team promoting and campaigning for residue management. Another key element that can have a significant impact on sustainability science development is adaptability. The change in the overall response taking place based on the impact and challenges that govern the overall problem is a good approach to the management of biomass residues.

4.2. Adaptability

Adaptability is a critical aspect of sustainability research, because it allows a system or society to adjust and respond to changes in the environment or circumstances without compromising its ability to function effectively in the future. This is especially important for environmental sustainability, where quick and unpredictable changes, such as resource depletion and climate change, are becoming more frequent. Adaptability enables communities, ecosystems, and institutions to adjust sustainably and respond to these changes over time. Adaptability is a fundamental component of sustainability research, as it recognizes the dynamic nature of social and ecological systems and the need to anticipate and adapt to changing circumstances. The ability to adapt, learn, and innovate in response to changing conditions, as well as the ability to incorporate new information and perspectives into decision-making processes, is essential for adaptability. Resilience, or the ability of a system to withstand disturbances while maintaining its fundamental structure and function, is closely linked to adaptability. Effective adaptation to environmental changes and the ability to anticipate and prevent potential threats to human beings is crucial for achieving sustainability. Interdisciplinary approaches, which involve integrating information and perspectives from various disciplines, are essential in sustainability research, because the problems are complex and require knowledge from a wide range of fields, including the natural sciences, social sciences, and humanities [74]. The problem-solving approach is based on the evolution of complexity as a problem-solving mechanism that has the potential to address today's environmental challenges by using sustainability. Recent research implicates the development of complexity in the system of problem-solving mechanisms. The solution to the dilemma can be traced primarily from the knowledge of our historical position in complex situations and, secondly, from the energy to finance and address the problems and to find the solutions.

In sustainability science, adaptability and interdisciplinary approaches are closely linked, because interdisciplinary methods facilitate flexibility. By bringing together experts from diverse fields, interdisciplinary collaborations enable a more comprehensive understanding of sustainability challenges and the development of more effective solutions. These collaborations can also identify potential trade-offs and synergies between various sustainability objectives, guiding the creation of adaptive management systems. Additionally, creating adaptable strategies and solutions to address complex sustainability challenges requires interdisciplinary approaches. The concept of resilience further connects adaptability and transdisciplinary ideas, as resilience involves being able to adjust to changing circumstances and utilizing various knowledge and abilities to identify and implement effective solutions, requiring both adaptability and interdisciplinary methods [74]. Furthermore, adaptability and multidisciplinary studies are related because of the need for the ongoing improvement of sustainability science. As new challenges arise, sustainability science must remain open to new perspectives and be able to synthesize information from other fields to develop innovative solutions.

Some of the key dimensions of adaptability in sustainability science include flexibility, diversity, learning, and collaboration (Figure 3). The following sections try to explain the importance of these elements in the practice of residual management topics. Residue management is a critical component of sustainable agricultural practices, and its success depends on the key dimensions of adaptability in sustainability science. Residue management requires farmers to be flexible in their approaches to managing crop residues. This includes adapting to changing weather patterns, soil conditions, and crop yields. Farmers need to be able to adjust their residue management strategies accordingly, such as varying the timing and method of residue incorporation or removal. In addition, maintaining diversity in the types of crops grown and the residue management techniques used can help to build soil health and reduce erosion [75]. Learning from experience and new research is critical to improving residue management practices over time, since farmers need to stay informed about the latest techniques and technologies for managing residues, as well as the impacts of these practices on soil health, crop yields, and the environment [76].

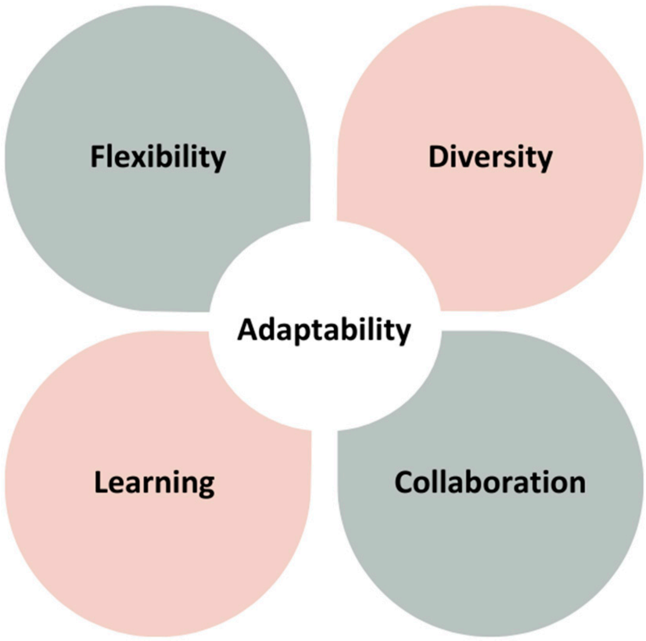

Figure 3. Dimensions of adaptability in sustainability science through the lens of systems thinking.

Residue management is a complex issue that requires collaboration among farmers, researchers, and other stakeholders. Farmers can work together to share knowledge and resources, develop new residue management techniques, and advocate for policies that support sustainable residue management practices. Collaboration between farmers and researchers can also lead to the development of new tools and technologies for residue management. Hence, the key dimensions of adaptability in sustainability science, such as flexibility, diversity, learning, and collaboration, are all critical to successful residue management. By embracing these principles, farmers can build sustainable residue management systems that promote soil health, reduce erosion, and improve the overall sustainability of their agricultural operations.

Additionally, through adaptability, changes in policies and governance that may influence residue management strategies can be identified and appropriate adjustments made to promote regulatory compliance [77]. Biomass residues from farms and forestry are largely produced in the local communities, and through adaptability and considering the environmental and socioeconomic conditions, biomass residue management ought to be adapted in the local context. Through adaptability, residue management practices can be tailored to suit the needs and interests of local biomass residue producers [77]. That would mean having the practices designed for the characteristics of the biomass and the needs of the local community. Again, interdisciplinary collaboration and systems thinking are critical for such area-specific biomass residue practices, since formulating an appropriate design will call for critical thinking and innovation. The overall review helped in developing insights into the current challenges, knowledge gaps, and principal elements of sustainability science, which can help to address this issue.

5. Conclusions

Integrating systems thinking with sustainability science in the management of biomass residues can lead to more effective and sustainable practices that address the complexities of modern waste systems. This comprehensive approach helps in developing the best practices that consider the entire lifecycle of materials from production to disposal, thus ensuring that each stage is optimized for sustainability. This approach also involves a diverse group of stakeholders, including scientists, scholars, industries, communities, and policymakers. By understanding different perspectives, eco-friendly, comprehensive, flexible, and adaptable solutions for biomass residue management can be developed. It encourages collaboration across various sectors, such as agriculture, forestry, municipalities, and energy, to effectively address the complex challenges of waste management. The most effective interventions from this approach rely on data and systems modeling to predict outcomes. Additionally, systems thinking and sustainability science can support awareness programs that educate the public and businesses about their roles in waste management, decarbonization, and the circular economy.

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