Sorghum Straw Pellets: A Dispatchable Energy Source for Australia's Renewable Energy Transition

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Abstract

The transition towards renewable energy in Australia faces challenges due to the intermittent nature of solar and wind power. One potential solution is the utilisation of sorghum straw pellets, a by-product of a common crop. This review synthesises existing literature on sorghum biomass pelleting and evaluates the bioenergy potential of sorghum straw using data from the 2023 national variety trials sorghum harvest report and the Australian biomass for bioenergy assessment. The analysis indicates that the pelleting process can enhance the energy density of sorghum stubble from 3.7 GJ/m³ to 10.2 GJ/m³. Converting all available stubble into pellets could potentially generate up to 165.8 PJ/yr of bioenergy. This represents approximately 15.4% of Australia's existing agricultural resource potential (1077.5 PJ/yr) and 43.5% of the country's bioelectricity potential (380.9 PJ/yr). Compared to other bioenergy sources, sorghum straw pellets could potentially surpass cane bagasse (26.3%) and wood (23.4%) in contributing to Australia's bioelectricity potential. This potential could enable Australia to provide and export clean, reliable, and affordable energy while creating new income opportunities for sorghum growers. The review also addresses broader sustainability issues such as the "food versus fuel" debate, the protection of northern Australia's coastal water and marine ecosystem from agricultural runoff (particularly the Great Barrier Reef), and the sustainable use of abandoned mining sites. This study contributes to the discourse on achieving Australia's sustainable energy transition.

Highlights

☐ Estimates the availability of sorghum stubble for generating bioenergy.
☐ Characterises the quality of biomass for market-grade pelleting.
☐ Identifies the ash's chemistry as a challenge in developing reliable solid biofuels.
☐ Proposes solutions to manage excess ash in biomass.
☐ Provides benchmarking data for the emerging Australian bioenergy sector.

Keywords: bioenergy; biomass; cereal crop stubble; climate resilience; sustainability.

Word count: 8965

List of abbreviations

ABARES, Australian Bureau of Agricultural and Resource Economics and Sciences
ARC, Australian Research Council
ARIMA, autoregressive integrated moving average
A-UKFTA, Australia-United Kingdom Free Trade Agreement
CAGR, compound annual growth rate
CIT, conditional inference tree
CSIRO, Commonwealth Scientific and Industrial Research Organisation
GDP, gross domestic product
GEN 2, second-generation biofuels research and development
GJ, gigajoule
GW, gigawatt
GWh, gigawatt hour
GWP, global warming potential
HHV, higher heating value
HI, harvest index
IRENA, International Renewable Energy Agency
LRET, large-scale renewable energy target
NEM, National Energy Market
NSW, New South Wales
NUE, nutrient-use efficiency
NVT, national variety trials
OECD, Organisation for Economic Cooperation and Development
PEA, Plantation Energy Australia
PJ, petajoule
PV, photovoltaic
QLD, Queensland
RET, renewable energy target
SRES, small-scale renewable energy scheme

USD, United State dollar

1. Introduction

Australia is pursuing a transition towards renewable energy, with a long-term goal of achieving net-zero greenhouse gas emissions [1]. This strategic shift is designed to reduce reliance on fossil fuels and aligns with global agreements aimed at mitigating the adverse effects of climate change. In recent years, renewables have become more economically viable, outpacing coal, and addressing concerns about stranded assets [2]. Like many countries, Australia has been progressively adopting variable renewable energy technologies, such as solar PV and wind power plants [3]. As of 2024, renewable resources such as biomass, solar, wind, and hydro contributed to approximately 29.9% of Australia's total electricity generation (3208.4 GWh) in the NEM [4]. However, to ensure a smooth and successful energy transition on a global scale, it is imperative to increase the share of dispatchable renewable energy [5]. Dispatchable renewable energy can generate electricity even when solar and wind resources are low, thereby providing a consistent and reliable power supply [6]. Additionally, it has the potential to reduce the need for extensive transmission lines in the national grid, supporting the transition towards a resilience system where bioelectricity is supplied from various sources such as solar, wind, or hybrid (solar-biomass) farms on land, contributing to regional development [7].

Bioenergy, a form of dispatchable renewable energy, is anticipated to play a pivotal role in Australia's transition to renewable energy [8]. It can potentially produce various products, including biofuels and industrial process heat. These are particularly vital for sectors that face challenges in decarbonisation [9]. Moreover, bioenergy can generate electricity on demand, a unique advantage during periods of low solar and wind resources [10]. For instance, in regions where it rains for several days or during times of low wind, current battery resources may be exhausted. In such scenarios, rapidly dispatchable energy, like bioenergy, is required as a backup. This also applies to peak and extreme demand periods, such as during heatwaves [11]. This is especially relevant to business models based on micro-grids. In these models, a group of participants located in close proximity connect their individual energy loads and generation capacities to form a micro-grid. This micro-grid can include a mix of renewable energy sources and (bio)diesel power generation. It connects to the NEM at a single point, providing backup access to the main grid as and when required. It also serves as a pathway for exporting surplus power generation [12].

While some nations (e.g., Brazil and the U.S.) have already adopted bioenergy on a large scale, others, including Australia, are lagging in developing a bioenergy industry [13]. In 2021, bioenergy from biomass and renewable municipal solid waste contributed to approximately 3.8% of Australia's total energy supply, which is low compared to the median of 7.2% in other OECD countries [14]. One of the reasons for the underdeveloped bioenergy sector in Australia is the lack of information on the actual potential of bioenergy. Recognising this, the Australian Government commissioned a bioenergy roadmap in 2021 to promote the role of bioenergy in the energy transition [15]. To foster growth in Australia's bioenergy sector, it is crucial to strengthen infrastructure and understanding of various feedstocks and their potential benefits and opportunities for renewable energy generation. This involves exploring the potential for bioheat and bioelectricity derived from pellets made from agricultural crop residues, including bagasse from sugarcane industrial processing and stubble from cereals such as sorghum, wheat, barley, and millet.

In Australia, grain farmers generally leave the crop stubble and residue in the field after a harvest, in part to rejuvenate the soil and lessen erosion. However, there is significant potential for creating additional options for using crop residue as a circular energy solution in rural and regional Australia and creating additional sources of income for growers [16]. This aligns with the ambitions of the emerging Australian biofuels industry for the next decade. The objective is to transform these waste/by-products into high-tech fuels of the future, thereby creating a wave of new income streams for Australian farmers. Despite these prospects, Australia has not yet exploited the potential of bioenergy, particularly from sorghum stubble. This presents an opportunity for agriculture to play a pivotal role in energy supply while also addressing the competing demands of food and energy security.

Biomass, particularly when derived from agricultural residues and energy crops, frequently exhibits irregular granulometry and size and lower (bulk and particle) density than coal or woody resources [17]. These characteristics lead to handling, storage, and transportation challenges. They also result in processing inefficiencies and larger conversion equipment/reactor volumes, leading to additional costs for biomass processing, logistics and utilisation. The quality of solid biofuels, such as pellets derived from agricultural biomass, is also often inferior in physical and chemical properties compared to those from forestry biomass. By characterising biomass, these parameters can be controlled to improve the quality of pellets to be fit for purpose in bioenergy applications [18].

Australia's feedstocks and WTE materials hold significant potential for bioenergy production. However, this potential is not fully understood, leading to uncertainties within the sector. This is a key finding of Australia's bioenergy roadmap [15]. The roadmap also outlines the critical factors influencing biomass conversion into solid fuels for industrial heat and bioelectricity generation. These include moisture content, ash content, and energy density. High moisture levels can diminish the energy value of biomass and compromise its storage quality [19]. Ash content can lead to equipment damage during combustion and gasification, necessitating its capture and disposal [20]. As such, low-ash biomass is preferred. Moreover, due to the lower bulk and energy densities of biomass compared to fossil fuels, a larger quantity of biomass is needed to produce the same amount of energy [21].

Understanding these factors is crucial for effectively utilising biomass and WTE materials in Australia.

Sorghum stubble, in particular, is a promising biomass feedstock for producing non-wood fuel pellets, a type of solid biofuel, in Australia. However, comprehensive information on its availability, quality, and potential for renewable energy generation is poorly integrated. To fill this gap, this literature review was conducted to address the following objectives: i) assess the supply and characteristics of sorghum stubble for pellet production, ii) evaluate the performance and benefits of this non-woody solid biofuel for renewable energy generation, and iii) identify potential sustainability opportunities and challenges for resilient sorghum-based bioenergy systems and products.

The review paper is organised into six main sections, starting with background to introduce the topic and the objectives of this review, followed by (2) a review strategy, which describes the methodology, and (3) a discussion of the national bioenergy landscape. It is followed by a detailed section on (4) the potential of sorghum for bioenergy and (5) a commentary on the sustainability trade-off of using sorghum. The last (6) conclusion section summarises the main findings and implications of the review and suggests areas for further research or policy intervention.

2. Review Strategy

2.1. Australian Bioenergy Landscape and Sorghum Biomass Pelleting

To gain a comprehensive understanding of the Australian bioenergy sector, this research examined its segments (e.g., diversity and availability of bioresources, biomass-to-fuel conversion technologies, and solid fuel applications) and identified potential markets for solid biomass fuel. Key documents reviewed include Australia`s bioenergy roadmap [15], including its appendices ‘market activity and opportunities’, ‘resource availability, and production pathways’. Moreover, national technical reports such as Net Zero Australia: how to make net zero happen [1], Clean Energy Australia [22], Implementation of bioenergy in Australia [14], Australian energy update [3], Australian sustainable energy: zero carbon Australia stationary plan [23], Overview of bioenergy in Australia [24], and biomass for bioenergy project–pellets factsheet [25], were referenced. A thorough literature search was conducted on sorghum biomass pelleting using databases such as Web of Sciences and Scopus. A broad search string, ALL= (“sorghum st*” AND “pellet*” OR “solid biofuel” OR “dens*”), was used to capture variations in terminology. Notably, ‘sorghum st*’ included ‘straw’, ‘stem’, or ‘stubble’, while ‘pellet*’ covered ‘pellet fuel’, ‘pelletising’, or ‘pelletizing’. The term ‘straw’ was used for pelleting and ‘stubble’ for biomass availability, aligning with international and Australian literature preferences. Articles were screened based on their relevance to sorghum pelleting for biofuel, excluding those on animal feed. Duplicate entries were removed using EndNote.

2.2. Assessing Technical Quality and Calorific Value of Sorghum Pellets

To assess the technical quality of sorghum biomass and its fuel pellet, bibliometric data from 17 peer-reviewed papers (**Supplementary Table S1**) that met the selection criteria out of 23 initially identified were analysed. Additionally, raw and pelleted sorghum biomass was compared with other relevant WTE materials, such as white wood, one of the emerging feedstocks in NSW. Selected peer-reviewed papers and the Biomass Quality Database [26] were utilised due to the limited Australian literature on the subject. The calorific value of raw and pelleted sorghum straw and its potential for renewable energy generation in Australia were estimated using Dulong's formula based on the material's chemical composition [17]. The focus was on the elemental constituents (C, H, N, S, and O) that affect heating values (**Supplementary Figure S1).**

2.3. Estimation of Biomass Availability, Bioenergy Potential, and Analysis of Ash Chemistry

The quantity of stubble that could be used for pellet fuel and bioenergy from grain sorghum harvest data in QLD, NSW, and WA was estimated using the 2023 NVT sorghum harvest report [27] and considering a harvest index (HI = 0.46) indicated in Unkovich et al. [28] and adopted in the Australian biomass for bioenergy assessment [29]. The energy density and potential bioenergy contribution of the raw stubble were calculated using a bulk density of 223.7 kg/m^3 and HHV of 14.1–17.9 MJ/kg. For the pelleted stubble, bulk densities of 439.5–626 kg/m^3 and HHV of 15.7–17.4 MJ/kg were considered, according to selected studies for the technical evaluation of sorghum-based fuel pellets (**Supplementary Table S1**) Scenarios utilising 10%, 25%, 50%, or all of the stubble were considered to account for soil health, environmental impacts, and potential demand for the lignocellulosic bioresource by other sectors. In addition to the energy potential, the ash chemistry of sorghum straw pellet fuel was examined to identify potential risks of slagging or fouling during combustion [20]. Furthermore, the bioelectricity potential of sorghum stubble was analysed under positive, neutral, and negative scenarios based on a 30-year time series (1990-2022) of bioelectricity generation from biomass resources, including bagasse and wood [30]. In the optimistic scenario, it was assumed that the bioenergy industry would experience rapid growth driven by technological advancements, policy support, and private investment. In the neutral scenario, it was assumed that the bioenergy industry would progress moderately, with a balanced rate of development, uptake, and breakthroughs. In the adverse scenario, it was assumed that the bioenergy industry would face major challenges, such as a lack of understanding, uncertainty, governance issues, and an immature supply chain. It was also considered that the bioenergy uptake and costs would remain stagnant and that government investment would be limited.

2.4. Statistical Analysis and Data Visualization

The analysis focused on two fundamental aspects: the quantity and quality of the sorghum stubble. A CIT analysis was conducted to assess the quantity of sorghum stubble available for biomass pellet production. Conditional inference tree is a non-parametric regression method capable of handling intricate interactions and nonlinear relationships. The analysis considered key sorghum-producing regions in Australia, considering location, climate, and hybrid type as influential factors. Contour plots were developed to visualise the spatial distribution of stubble availability and to explore the effects of varying stubble-to-pellet conversion rates. An ARIMA model was applied to the time series of bioelectricity generation from cane bagasse and wood to forecast renewable energy generation by the 2030s. The potential contribution from unprocessed and treated sorghum was included in the model to visualise its role in securing a reliable bioenergy sector. Ash chemistry, as well as proximate and ultimate properties, were considered to determine the biomass quality and suitability for combustion. The proportions of acid and basic oxides in the ash were illustrated with ternary charts. Critical thresholds for these indices and the slagging viscosity index were identified, serving as indicators of material compatibility with biomass thermal conversion equipment. Ternary charts were also used to illustrate the volatile matter, fixed carbon, and ash content of the pellets, accompanied by a scale for the volatile fuel index, reflecting the fuel's reactivity during combustion (**Supplementary Figure S1**). A van Krevelen diagram was designed to visualise changes in carbon concentration in sorghum straw after torrefaction and its contribution to developing a highly energetic and hydrophobic solid biofuel similar to coal (**Supplementary Figure S2**). The data analysis was conducted using Python and R. Specific packages, including *Party*, *Ternary*, *ggplot2*, and *forecast*, were used for CIT modelling, ternary charts, contour plots, and ARIMA modelling, respectively.

3. Bioenergy in Australia: Potential, Markets and Challenges

In 2021, bioenergy accounted for 3.8% of the nation's renewable electricity and 1.3% of total electricity generation. Australia's bioenergy roadmap [15] highlights bioenergy's potential, estimating it could provide up to 20% of Australia's energy by the 2050s. However, several challenges, such as securing sustainable feedstock, scaling up production, and reducing costs and emissions, need to be addressed to achieve this target.

Currently, bioenergy, especially from solid biomass and biogas, meets 12% of Australia's energy demand and is projected to rise to 33% by the 2030s. Industries such as sugar, food, wood, pulp, and paper use bioenergy from waste, creating a circular and sustainable energy system. Moreover, bioenergy's potential in bioelectricity is considerable, with the possibility of increasing from 1.3% to 9% of grid power and 11% of off-grid power by the 2050s [15]. Australia's bioenergy potential is immense, estimated at over 2600 PJ per year, enough to cover 40% of the current primary energy supply. Queensland and NSW are leading in bioelectricity production, mainly using bagasse, wood waste, and landfill gas [1].

A key factor to consider is the opportunity cost associated with using agricultural land for bioenergy production instead of food cultivation. The decision-making of farmers will likely depend on the economic feasibility, with a potential shift towards bioenergy if it proves to be more profitable. For example, if monetary value is attached to stubble, farmers might prefer to cultivate sorghum over other crops. If the financial return from stubble is substantial, they might opt for taller crops, which, while reducing the HI, would yield more stubble. However, this could necessitate increased inputs, thereby impacting the environment and escalating production costs. The challenges faced include the absence of stubble cover, which could lead to increased erosion and a decrease in soil carbon. If a price is established for soil carbon, it might be more beneficial for farmers to refrain from harvesting the stubble [29].

The Australia's bioenergy roadmap [15] recommends using resilient crops such as sorghum for bioenergy, allowing intercropping with food crops and using cereal residues. This approach, which avoids additional land clearance or conversion of food production areas, corresponds with technological advances such as pelleting to improve energy density. Integrating sorghum into existing agricultural systems can increase efficiency and profitability, addressing deforestation and greenhouse gas emissions issues, especially in QLD and NSW, which have been identified as deforestation 'fronts' in the country in the national inventory report [31]. Adopting sustainable practices and innovative solutions such as non-woody fuel pellets from sorghum stubble has the potential for the bioenergy sector's sustained growth and minimal environmental impact.

3.1. Pellet Fuel Integration: Policies and Business Models

The Australia's bioenergy roadmap [15] outlines a strategic vision for the country's bioenergy sector to advance renewable energy and reduce emissions. However, unlike Brazil and the U.S., where biofuels have grown steadily with long-term policy support, Australia has a limited bioenergy landscape, especially for bioheat and bioelectricity from biomass-to-solid fuels.

The RET scheme is one of the few policies that indirectly supports bioheat by incentivising renewable electricity generation [14]. The RET scheme has two components: the LRET for large-scale projects and the SRES for individual and business systems. These systems can include pellet fuel, which can power micro-grids that combine multiple energy sources and operate on or off the national grid but can connect to the grid if and when required [12].

Pellet fuel can offer a reliable and flexible source of renewable energy, particularly in regions with limited or unstable access to other energy sources. The energy security board [32] projects that Australia will require 6 to 19 GW/yr of rapidly dispatchable generation by 2040 to balance the influx of variable renewable energy. This capacity is over six times that of the largest generator in the national electricity market, which is expected to lose most of its coal-fired generation by 2040. Bioelectricity generated from fuel pellets could help bridge this gap. Our calculations suggest that if 50% of the potentially available sorghum stubble were dedicated to bioenergy, it could generate 0.9 GW/yr. Pelleting the material could increase this output to 2.6 GW/yr, and torrefaction could further boost it to 4.4 GW/yr. This could potentially contribute, along with other sources, to meeting Australia’s demand for rapidly dispatchable electricity. However, these estimates depend on a robust supply chain and efficient technology conversion processes in terms of cost and energy.

3.2. Global Trends in Trade and Australia's Niche in Non-Wood Pellet Fuel

Pellets offer ease in handling, storage, transportation, and usage, particularly in industrial and residential heat or power applications. Globally, wood pellets are the predominant type, with a production of approximately 46.4 million tons in 2022 and a CAGR of 9.4% (**Figure 1**). This growth is driven by the increasing bioenergy demand amid efforts to mitigate climate change. Projections suggest an increase to 64 million tons and possibly 120 million tons under a high-demand scenario by the 2050s [33].

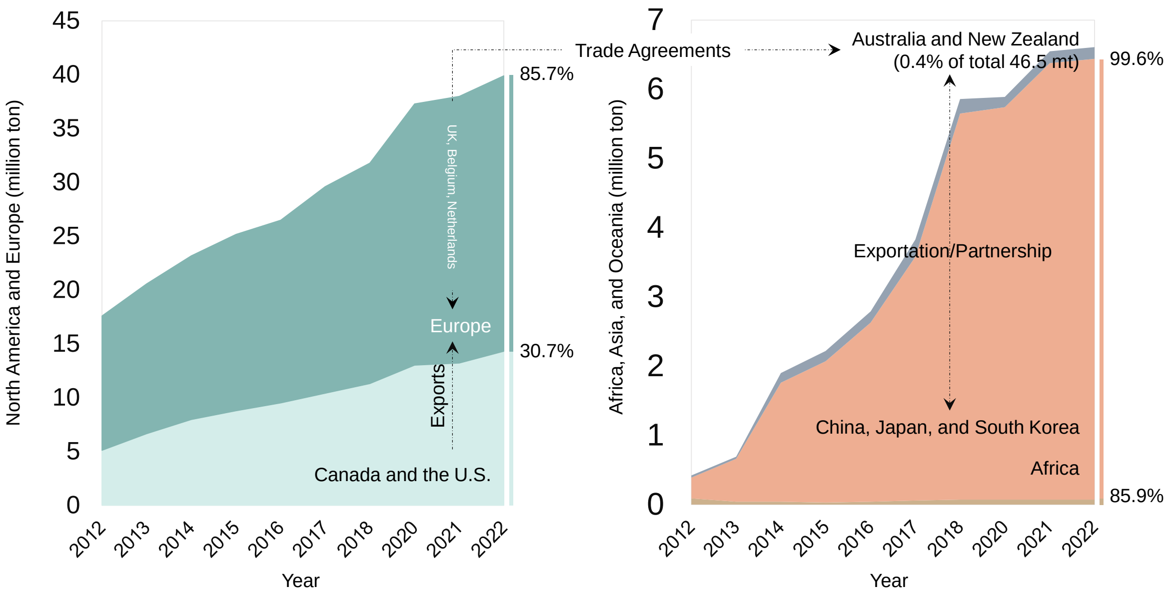

Figure 1. Global trends in wood pellet production. The figure shows the trend of global wood pellet production from 2012 to 2022 (excluding 2019 due to the COVID-19 pandemic) in two subplots. The left subplot compares the production in North America and Europe, which are the major producers of wood pellets. The right subplot compares the production in Africa, Asia, and Oceania, which are emerging markets with potential for growth. Arrows represent the international trade activities of wood pellets. The data is adapted from the World Bioenergy Association [34].

The EU and North America, mainly producing wood pellets, dominate the global pellet industry, accounting for 86% of the world's output [34]. In 2022, Australia and New Zealand produced 1.7 million tons of pellets, only 0.4% of the global total, but with an annual growth rate of 42.7%. The Asian market, particularly China, Japan, and South Korea, displays a burgeoning demand for pellets. The Russian-Ukrainian conflict has also disrupted the wood pellet supplies to Europe, previously sourced substantially from Russia. This supply gap presents an opportunity for Australia to export both wood and non-wood pellets, leveraging its diverse feedstock.

Australia is rich in non-wood feedstocks, offering a unique opportunity in the pellet industry, either domestically or internationally. For instance, sorghum straw can be processed for bioenergy, and with a densification factor of 2.8-4.6, it could significantly cut transportation costs. A common challenge with agricultural commodities is their high volume coupled with low heating value, which restricts cost-effective transportation at low volumes. This issue can be mitigated by pelletisation. Biomass feedstocks, despite having a lower energy density (15-20 GJ/t) than fossil fuels, can achieve an energy density of 10.2-17 GJ/m^3 through processing techniques like torrefaction and pelletisation. This enhancement, as reported by the IRENA, could potentially halve transportation costs [35]. Looking ahead to 2030, IRENA estimates that the cost of shipping biomass from Australia to Japan will range between 0.9 and 3.6 USD/GJ. Increased energy density could render energy transportation more cost-effective, supporting the global shift from fossil fuels to sustainable energy sources.

Despite its nascent domestic pellet industry, mainly exporting to Japan (91%) and China (9.3%), Australia stands to capitalise on the rising demand for non-wood pellets internationally. The A-UKFTA presents a strategic opportunity, eliminating tariffs on most Australian exports, including agricultural products [36]. The UK, a significant pellet consumer for power generation [37], could benefit from cleaner and cost-effective Australian non-wood pellets. The A-UKFTA also supports professional exchanges, potentially fostering innovation in the pellet industry. This agreement positions Australia to access new markets, especially in the UK, aiding the global shift towards a low-carbon economy. However, caution is advised, emphasising that exports of pellets from sorghum or other agriculture or forestry resources should not be raised until Australian energy security can be delivered—a viewpoint supported by economic models [38].

3.3. The Dynamics of the Pellet Industry in Australia

Australia is actively investing in research and development to support the growth of the pellet industry. For instance, the GEN 2 program backs innovative technologies and feedstocks that address a suitable, reliable, and sustainable bioenergy industry. The biomass for bioenergy project, funded by the NSW climate change fund, assesses various aspects of biomass cultivation, processing, storage, and co-firing with coal [39], including the environmental impact and feasibility of bioelectricity generation from solid biofuels.

In Australia, several companies are actively involved in the sustainable production of wood pellets from sustainably sourced biomass. One such company, Altus Renewables, operates both the Bundaberg Export Facility and the Tuan Project, which collectively have an annual capacity of 250 thousand tonnes. In addition, Altus is in the process of developing the Green Triangle Project, which is expected to yield an annual capacity of 500 thousand tonnes. Another significant player in this industry is PEA, which produces 125 thousand tonnes annually, all of which is exported to Belgium.

The Green Triangle Project by Altus Renewables is of particular interest due to its dual-purpose design. It is intended to serve both the export of renewable electricity and domestic consumption, despite the limited local demand. Plantation Energy Australia, conversely, is proactively exploring opportunities to cater to Asian markets, thereby extending its international reach beyond Belgium. The forestry sector is currently experiencing a demand shift from paper to energy, primarily influenced by Japan and South Korea. This shift underscores the evolving dynamics of both domestic and international activities in the wood pellet industry.

The domestic wood pellet market in Australia, which has potential, is currently facing challenges. These challenges could influence its domestic situation and international commitment to renewable electricity generation. The country's coal dependence and environmental issues are significant obstacles. In 2022, the Australian government decided to exclude materials from native forests for energy production from the renewable category [40]. This decision could have implications for the wood pellet industry, especially with the projected global demand of 36 million tons by 2027. Australia's initial goal to produce 3 million tons of pellets by 2027 may require the consideration of alternative strategies. One possible strategy is the use of sustainable, non-woody biomass. Sorghum-based pellets could be a viable alternative to wood pellets. Their use might be important for Australia to achieve its goals and fulfil its commitments, contributing to the national and global shift towards renewable energy.

In a balanced scenario where 50% of stubble is available for bioenergy generation, while still leaving material on the field to prevent soil erosion, the initial yield is 47.2 GJ/ha/yr. After pelleting, this yield increases to 132 GJ/ha/yr and further rises to 220 GJ/ha/yr after torrefaction. These figures highlight Australia's potential to enhance its utilisation of densified solid fuels through existing non-wood pellet mill plants. Noteworthy non-woody initiatives include the Burdekin Biomass Fuel Project, which exports non-wood pellets to Japan for electricity generation using bagasse from sugarcane production. Additionally, Bioghum, a Japanese company operating in Australia, focuses on advanced sorghum seed technology, aiming to serve domestic and Asia-Pacific markets with pellets derived from high-biomass sorghum hybrids.

Expansion initiatives of Altus, alongside the export-focused operations of PEA, Burdekin Biomass Project, and Bioghum, play a pivotal role in shaping Australia's wood pellet production landscape. However, the growing emphasis on exports in Australia's wood pellet industry raises questions about energy security. There is a need to re-evaluate Australia's energy security strategy, especially considering potential inefficiencies in the domestic infrastructure for wood pellet utilisation. The possibility of exporting wood pellets overseas could potentially undermine Australia's energy security. Nonetheless, if the domestic infrastructure proves to be efficient in utilising wood pellets, there is potential to prioritise domestic energy security needs over the export of renewable electricity in the form of pellets. This consideration is vital in formulating a balanced approach to Australia's energy strategy, addressing domestic and international energy security concerns.

4. Sorghum: A Versatile Crop for Australian Agriculture and Bioeconomy

Agriculture is a vital sector in Australia's economy, occupying 55% of the land and consuming 24% of the water resources. It accounts for 11.6% of the country's exports, 2.4% of its GDP, and 2.5% of its employment [41].

Sorghum is a robust and adaptable crop that thrives in various global climates, including regions susceptible to drought, flooding, and extreme temperatures (**Figure 2**). This versatile crop can be utilised for food, animal feed, and fuel production, and it requires less water and fertiliser compared to other crops, such as sugarcane [42]. In Australia, specifically, sorghum holds the title of the most crucial summer cereal grain. The favourable La Niña weather cycle in 2021-22, which enhanced irrigation access, led to a 62% increase in sorghum production, reaching a total of 2.6 million tons [41]. The majority of sorghum is cultivated in the north-eastern cropping zone of Australia, particularly in QLD and NSW, which contribute to 99.9% of the national sorghum output.

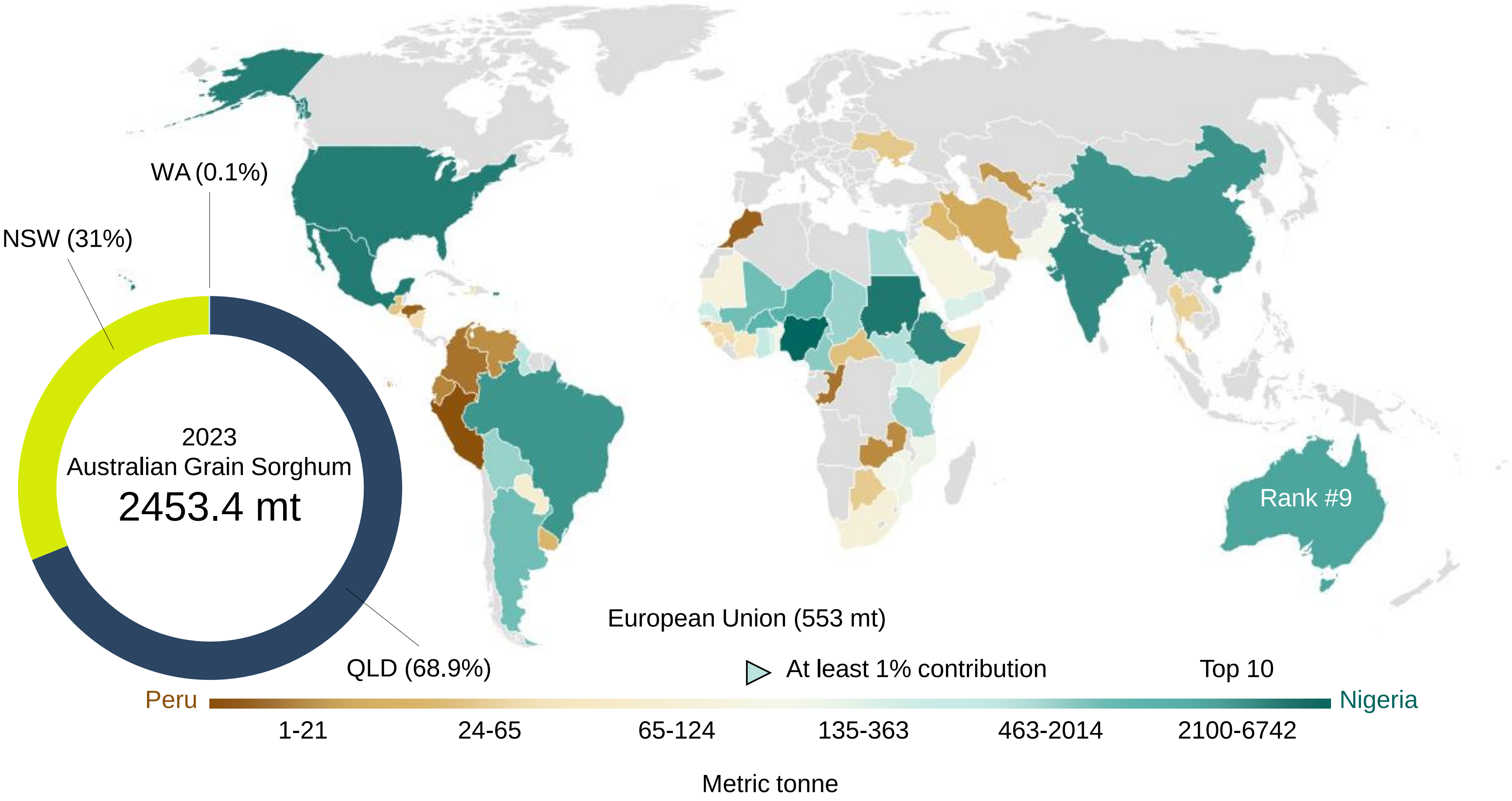

Figure 2. Global and regional trends in sorghum production volumes (in metric tonnes) for the 2022/23 period. The colour scale represents production levels, with a triangular marker highlighting regions contributing at least 1% to global production, as is the case of EU. A donut subplot provides a view of the distribution of grain sorghum across Australia. The data is sourced from the USDA Foreign Agricultural Service [105] and ABARES [41].

Sorghum, a grain primarily used for livestock feed in Australia, is facing a potential reduction in its cultivation area as a result of climate-related challenges [41]. These include decreased soil moisture and increased temperatures, which make the current production areas less suitable for sorghum growth. This is despite the crop's resilience to harsh climatic conditions, such as a drier and hotter climate, a trait that outperforms other crops like wheat [43] and sugarcane [44]. To mitigate this issue, it is crucial to broaden the applications of sorghum beyond its traditional use as livestock feed. This could involve developing new commercial products derived from sorghum or using it in industries without being utilised before [45].

Sorghum is a water-efficient crop that can grow on lands unsuitable for most grains. Such marginal lands could offer new opportunities for sorghum cultivation, especially for bioenergy production. However, the water quality of these lands must be carefully assessed, as it may affect the growth and yield of sorghum. For example, mine pit lake water [46], which is often saline and acidic, may not be appropriate for food-grade crops but could be used for energy crops. To evaluate the potential of sorghum as a bioenergy feedstock in these conditions, factors such as nutrient content, mineral composition, and environmental impacts must be examined. This approach could address the challenge of limited production area and create a new source of renewable energy and income for sorghum farmers.

Sorghum is a versatile crop that can provide biomass, biofuels, and bioenergy, like other grasses and woody species. Sorghums have diverse types [47], each with specific uses and traits:

- Forage Sorghum: Rich in nutrients, it is suitable for livestock feed in various forms [42].
- Grain Sorghum: Used as a gluten-free cereal for animals and humans, it comes in diverse colours [42, 48, 49].
- Sweet Sorghum: It produces sugar, syrup, jaggery, and alcohol from both grain and stem. It has fermentable sugar and cellulose for bioethanol production [42, 49].
- High-Biomass Sorghum: Bred for more height, stem volume, and vegetative growth, it is a promising source of cellulosic biofuels, such as bioethanol. Its yield potential has been improved by genetic studies [42].
- Dual-Purpose Sorghum: Developed for both grain and fodder production, it has a high yield and quality of both products. It can improve food/feed and nutrition security and income of smallholder farmers in semi-arid regions. It has stay-green traits that enhance its drought tolerance and fodder value [48, 49].

The yield of sorghum, particularly high-biomass varieties, is influenced by factors such as stem volume, height, and diameter [50]. Under ideal conditions, these varieties have the potential to produce up to 61.1 tons of dry biomass per hectare in the U.S. [51]. In Australia, studies on the stem tissues of various sorghum varieties, including a wild line, have uncovered substantial cellulose and lignin content, making them desirable for biofuel production. Photoperiod-sensitive sorghums, whether wild or cultivated, have shown the potential to yield 36.9 tonnes of dry biomass per hectare in the Australian grain belt (**Table 1**). This makes them strong candidates for producing high-quality lignocellulosic biofuels [45]. However, it's important to note that most reported sorghum biomass yields, and chemical properties are based on small-scale experiments or samples. These may not accurately reflect the yield potential and quality of sorghums grown on a commercial scale, which remains limited, especially in Australia. Therefore, these yield figures should be interpreted with caution.

Table 1. Comparative analysis of biomass yield and quality characteristics across various sorghum groups, including forage, sweet, grain, and photoperiod-sensitive types, for biomass, biofuels, and bioenergy purposes

Characteristic	Forage	Sweet	Grain	Photoperiod-sensitive
Dry matter yield (t/ha)		21.3[a]	3.6[a]	36.9 [a] (AU); 38[b]-61.1[c] (U.S.)
Height (m)[d]	1.8-3.6	2.4-3	0.6-1.2	2.4-6
Diameter (mm)[a]		14	17	13
Water (%)[a]		68	66	63
Cellulose (%)[e]	29.5	26.3	27.6-39.6	29.3
Hemicellulose (%)[e]	20.5	20	15-19.4	26.3
Lignin (%)[e]	8.6	7.1	10.2-15.4	7.6
Ash (%) [f]	5.4-10.9	2.6-10.2	6.3-11.3	2.3-9.9

[a] Byrt et al. [45], [b] Meki et al. [90], [c] Snider et al. [51],[d] Silva et al. [50], [e] Rooney et al. [52], Stefaniak et al [91].

4.1. Energy Densification of Sorghum Biomass: How Composition and Structure Matter

Sorghum biomass, primarily composed of cell walls, contains complex carbohydrates like cellulose, hemicellulose, and lignin that provide structural rigidity [52]. Additional components include proteins, starch, and minerals such as silica. The composition varies with the plant's genetics, growth stage, and environment, influencing the densification and combustion of biomass for energy production [53].

Cellulose, a long glucose chain, has crystalline and amorphous regions [54]. Hemicellulose consists of shorter, branched chains of sugars like arabinose and xylose [55], while lignin is a highly branched, irregular phenolic polymer [56]. The specific oxygen, hydrogen, and carbon ratios in these components affect their thermal decomposition. Hemicellulose decomposes at the lowest temperature, followed by cellulose and lignin [57].

Biomass combustion relies on carbon, hydrogen, and oxygen. Carbon provides heat, hydrogen enhances heat output, and oxygen aids combustion but reduces energy value. Compared to coal, biomass has less carbon, nitrogen, and sulphur but more hydrogen and oxygen. It also contains more moisture and ash, reducing its calorific value. Hence, densification and drying are necessary before combustion to enhance energy efficiency. Torrefaction, a thermal pre-treatment, improves biomass quality by ‘coalification’ [56].

The atomic ratios of raw sorghum biomass, specifically O/C (0.7-1.2) and H/C (1.4-1.7), significantly influence combustion properties. Torrefaction, a thermochemical process, alters the biomass composition, leading to mild carbonisation. This process reduces moisture and light volatiles, retaining more carbon and reducing elements with higher hydrogen and oxygen proportions. Consequently, the atomic O/C and H/C ratios decrease to 0.5–0.6 and 0.9–1.3, respectively (**Supplementary Figure S1**). Torrefaction also affects the volatile fuel index (VFI) of sorghum biomass, a key parameter for evaluating combustion characteristics. The VFI, linked to the specific proximate compositions of forage and sweet sorghums, quantifies the combustible volatile content in the biomass (**Supplementary Figure S2**). These differences result in varying VFIs, offering insights into potential combustion efficiency and energy release. Balanced O/C and H/C atomic ratios and a consistent VFI make sorghum biomass a reliable biofuel option, competitive with traditional fossil fuels (**Supplementary Figure S2**).

Comparative analysis with materials in the CSIRO’s biomass quality database [26] underscores sorghum’s potential as a solid biofuel. For instance, dogwood residue and cane bagasse from Australian samples serve as reference points. Dogwood residue has a VFI of 7.7, indicating high combustible volatile content, while cane bagasse has a VFI of 1.3, suggesting a slower, less intensive combustion process. Despite its lower VFI, cane bagasse’s higher oxygen concentration limits its HHV to 18.5 MJ/kg. A similar high-oxygenated feedstock scenario is observed in sorghum biomass, reflecting HHV between 16-19 MJ/kg, which can be significantly increased to 20-23 MJ/kg through torrefaction (**Supplementary Figure S1**).

Understanding and optimising the atomic ratios of O/C and H/C, and VFI through torrefaction not only contribute to the efficient utilisation of sorghum biomass in residential and commercial applications but also pave the way for sustainable and environmentally friendly energy solutions. Balanced O/C and H/C atomic ratios and a consistent VFI make sorghum biomass a reliable biofuel option, competitive with traditional fossil fuels (**Supplementary Figure S2**).

4.2. Stubble Availability for Pellet Fuels for Bioenergy Generation

Agricultural practices in Australia often lead to abundant agricultural residues, such as sorghum stubble, with potential for conversion into biofuels and providing additional benefits for farmers and the environment. However, the availability and feasibility of using these residues for bioenergy production are not well quantified and documented.

In a study conducted by Middelhoff et al. [5], the national volume of cereal stubble, including sorghum, was estimated using a combination of the HI method and remote geographical mapping. Their calculations revealed that cereal stubble has the potential to yield a substantial 28.6 million tons of biomass annually. Notably, NSW and WA exhibited the highest quantities of this valuable resource, aligning with predictions from Net Zero Australia's mobilisation report [1]. According to this report, by 2050, Australia has the capacity to generate approximately 600 PJ/yr of renewable bioenergy from biomass resources, with the primary distribution across QLD, NSW, and WA. However, this potential is significantly constrained to 60 PJ/yr due to competition with food production, land revegetation, and soil health preservation. To achieve a net zero bioenergy outcome, the report emphasises the critical importance of focusing on technologies that enhance these scenarios, as exemplified in this study through pelleting and torrefaction.

While using the same HI approach but harnessing updated data from the 2023 NVT sorghum harvest report [27] and the Australian biomass for bioenergy assessment [29], this study found that QLD, NSW, and WA could collectively produce approximately 3.6 million tons of sorghum stubble annually on 671 thousand hectares, with north-western NSW (Liverpool Plains) being the most productive region (**Figure 3**). By allocating 50% of the sorghum stubble (1.8 million tons) for bioenergy purposes and retaining the remainder for soil incorporation, trade-offs can be reduced, and multiple challenges related to energy and soil health can be addressed. A decision-tree framework was used to identify the factors that affect grain sorghum stubble yield potential. In addition, the conditional inference technique was also used to find the most important predictors of yield potential.

It was found that the region was the main factor affecting stubble yield, reflecting the influence of climate, soil, and other variations on crop performance. Within each region, specific sub-factors, such as hybrid choice, were also found to affect yield potential. This shows that sorghum responds specifically to environments and that cultivar selection should be based on local conditions. It was also found that WA (Ord) had the second-highest stubble production among regions (6.7 t/ha), suggesting that this area could provide biomass for various uses. The model proposed in this study can help stakeholders to choose the best location and hybrids for sourcing sorghum biomass and to optimise feedstock for bioenergy production.

Despite the significant potential of grain sorghum stubble for bioenergy, as highlighted by Middelhoff et al. [5], there are currently no dedicated bioenergy plants for processing this biomass into pellet fuel. An alternative approach suggests leveraging existing infrastructure designed for processing sugarcane bagasse or wood residues. This strategy, which involves mapping key processing plants across QLD, NSW, and WA, provides a practical path forward for integrating sorghum straw into the bioenergy supply chain. However, to accommodate the unique properties of sorghum straw, such as its grindability, it may be necessary to adapt existing bioenergy plants or create new ones.

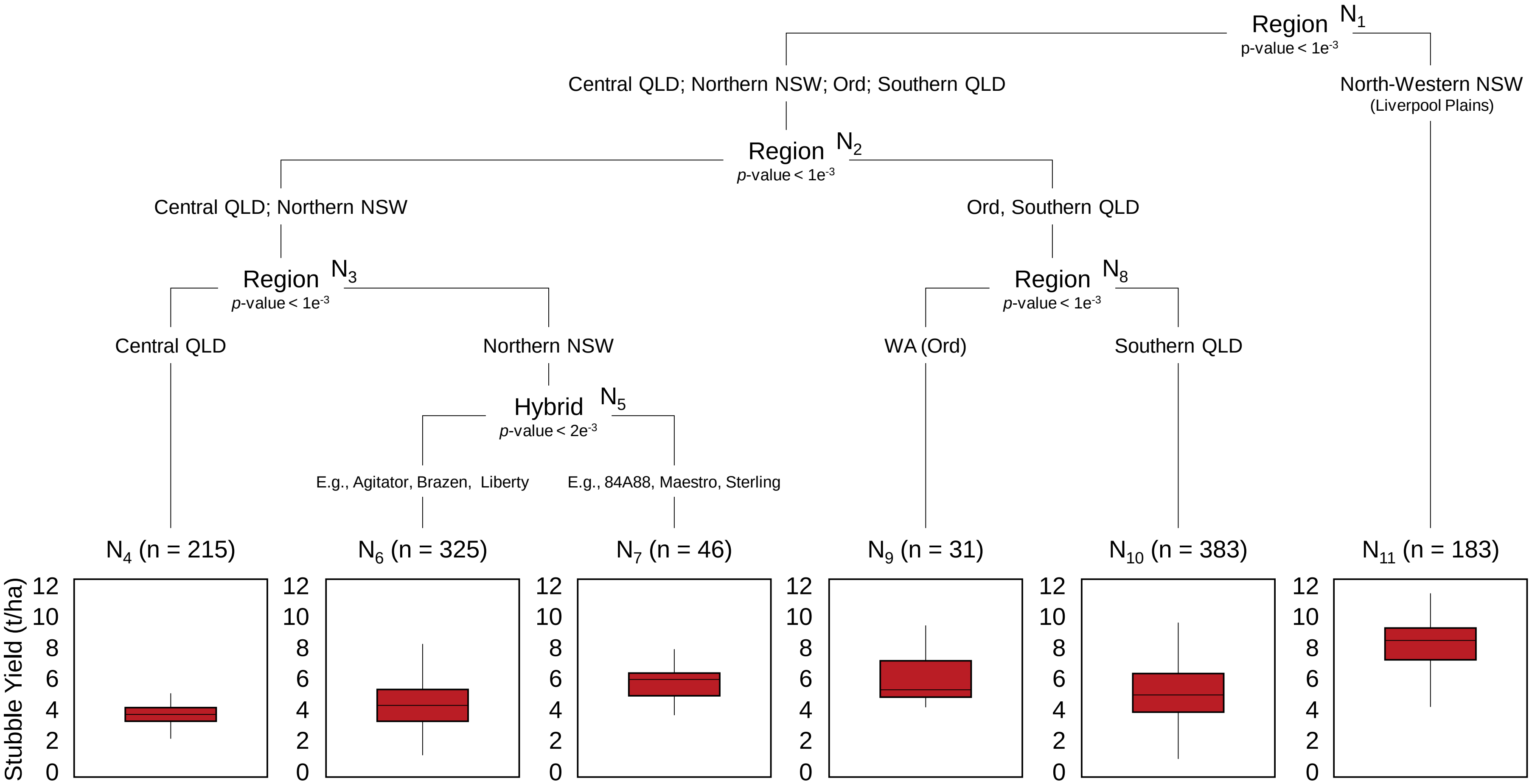

Figure 3. Factors influencing sorghum stubble yield in Australia by CIT model. The model investigates the influence of predictors such as state, region, and varieties on sorghum stubble yield. Each node in the tree-decision diagram signifies a decision point based on these predictors. The paths stemming from these nodes represent the decision outcomes, leading to the predicted stubble yield. Accompanying box and whisker diagrams provide a statistical summary of the stubble yield data.

The feasibility of such investments in processing, particularly in common user facilities, depends on the existence of demand. Therefore, securing contracts for pellets becomes a critical factor, as exemplified by Sojitz Corporation [58], where pellets are intended for use in their steel mill furnaces or those of their partners. Furthermore, the accessibility of sorghum material in the field with current technology/equipment is an important consideration for promoting sorghum-based pellets in Australia, even though it is not directly incorporated in the hierarchical modelling. This nuanced understanding is crucial for establishing a seamless supply chain for sorghum biomass, a key component in the production of pellet fuel for renewable energy generation.

4.3. Sorghum Straw Fuel Pellet

4.3.1. Potential Contribution to Australian Renewable Energy Generation

The energy density of sorghum straw, initially at 3.7 GJ/m^3, can be amplified to 10.2 GJ/m^3 through pelleting. If all available stubble undergoes pelleting, it could generate a significant 165.8 PJ/yr of bioenergy (**Figure 4**). This figure is approximately 15.4% of Australia's existing agriculture resource potential for bioenergy (1077.5 PJ/yr). Additionally, it could contribute 43.3% to Australia’s bioelectricity potential (380.9 PJ/yr), which is competitive with the collective contribution from cane bagasse and wood (189 PJ/yr). The raw stubble could also contribute 59.9 PJ/yr of bioenergy at the same rate, about 15.7% of the current bioelectricity potential. Even if only 50% of the stubble potentially available for bioenergy is pelleted, with the remainder dedicated to soil health maintenance or enhancement, it could contribute 21.7% to the existing bioelectricity potential in Australia. However, infrastructure, logistic efficiency, and the cost and capacity of pelletisation plants need to be evaluated to realise this potential.

This potential could strengthen Australia’s position to provide abundant, clean, reliable energy domestically at affordable prices. It could also cater to international markets by meeting their escalating demands for solid biofuels and renewable energy generation. These factors are pivotal in ensuring the nation’s energy security, economic growth, and prosperity. This could open new avenues for sorghum growers to profit from an additional income source by partially dedicating their stubble to fuel pellets. They could also receive incentives from the government or customers for their sustainable cereal crop waste management. This can positively impact their profits and their social license to operate.

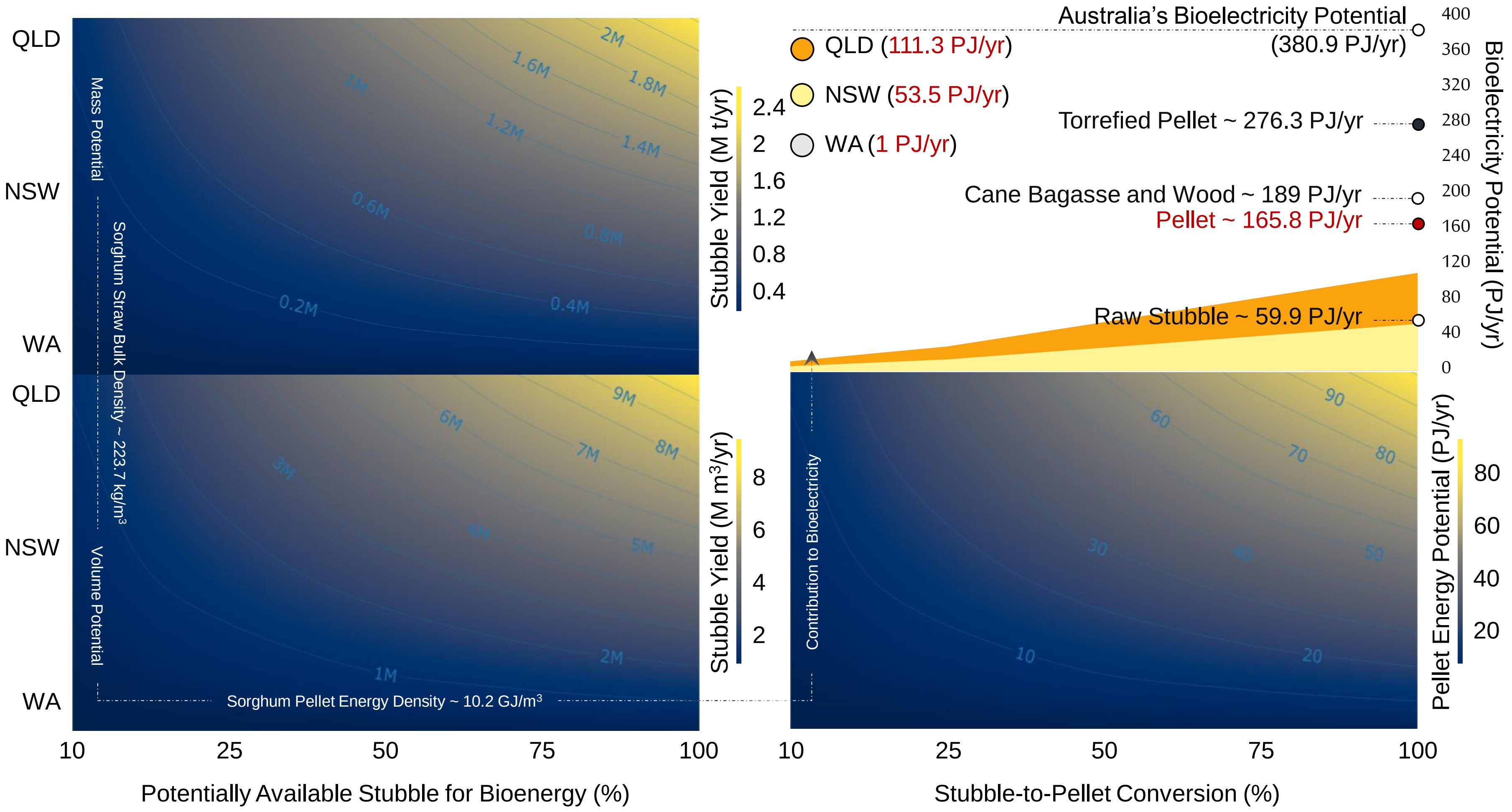

Figure 4. Potential availability of sorghum stubble. This figure presents a regional analysis of sorghum stubble's potential availability for energy densification and its role in Australia's bioelectricity generation. Contour plots depict annual yield, mass-to-volume conversion, and energy potential of sorghum pellets. A stacked area plot illustrates the contributions of QLD, NSW, and WA to stubble production and the performance of various forms of sorghum stubble compared to other bioenergy sources.

To provide a comparative analysis, this study includes the bioelectricity generation from cane bagasse and wood over a long-term period, forecasting their potential until 2030 (**Figure 5**). In an optimistic scenario, with industry-wide advancements and substantial investments, these resources could generate a significant 7108 GWh of bioelectricity. This projection, however, depends on increased adoption, cost reductions, and effective collaboration between industry and government. In contrast, a pessimistic scenario, marked by limited uptake, stagnation in costs, and lack of support, could result in a mere 168 GWh. This study also examined the bioelectricity potential of sorghum stubble, assuming that 50% of the available residue is used for bioenergy. In a balanced scenario, sorghum stubble could contribute an additional 7000 GWh to the bioelectricity mix, improving the combined output of cane bagasse and wood, estimated at 1818 GWh. If sorghum stubble is processed into pellets or torrefied, its bioelectricity output could increase to 19000 GWh or 32000 GWh, respectively.

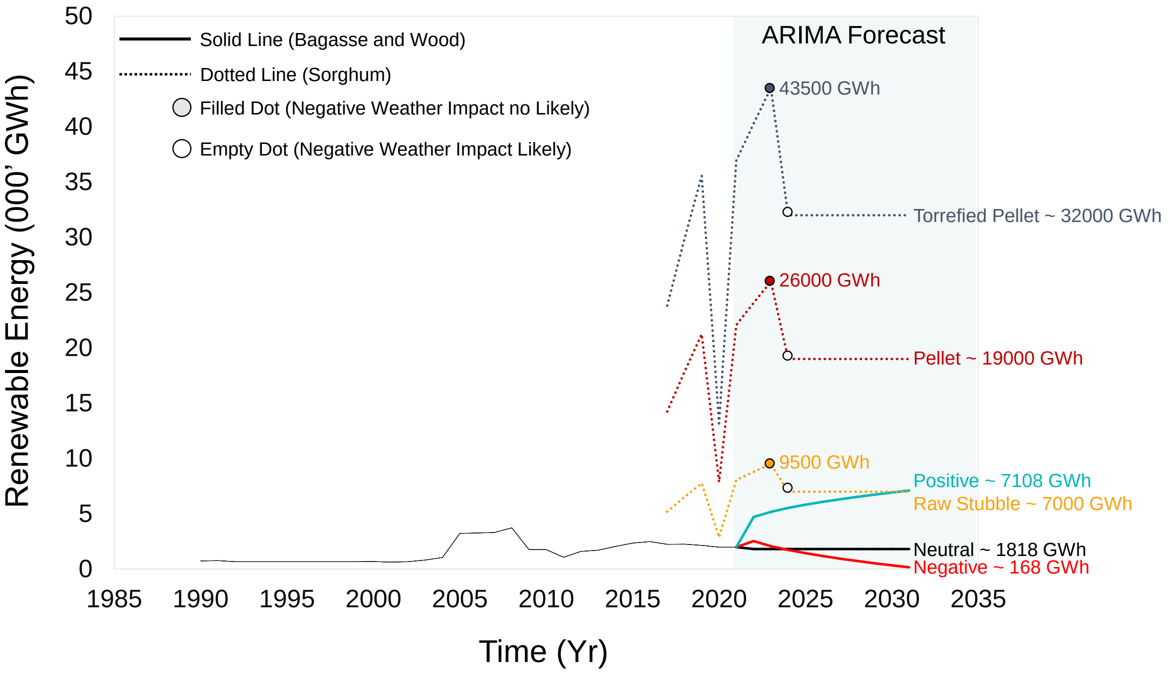

Figure 5. Bioelectricity generation in Australia. This figure traces and projects bioelectricity generation from 1990 to the 2030s, focusing on cane bagasse, wood, and various forms of sorghum stubble at 50% availability for bioenergy generation. The graph, with years on the x-axis and bioenergy generation in gigawatts per hour on the y-axis, compares scenarios of sorghum's varying impacts on Australia's bioenergy sector.

Models with a high proportion of renewable supply suggest that augmenting the capacity of dispatchable renewable energy sources, such as bioenergy, could lead to a reduction in the total cost of installed capacity. For example, a study by Li et al. [6] discovered that an increase in bioenergy capacity by a factor of five to fifteen could potentially decrease the cost of future renewable (solar-biomass) energy systems by 11 to 40%. The authors underscored that, given the current biomass capacity of 1.7 GWh installed in Australia, a 100% national renewable energy supply could be achieved with a system installed capacity of approximately 146–148 GWh at a levelized cost of electricity. This could be realised through the utilisation of sorghum stubble, regardless of the form (raw, pelleted, or torrefied), which could generate a significant surplus and serve as an additional revenue stream for stakeholders.

Notably, sorghum stubble and its solid biofuel, either pelleted or torrefied, holds great promise as a biofuel for Australia's bioelectricity sector, potentially diversifying and bolstering the reliability of dispatchable renewable energy sources. However, external factors such as weather and soil conditions pose potential challenges [59]. The ABARES [41] predicts below-average rainfall and elevated temperatures in northern cropping regions, particularly for the 2023-24 season. This forecast anticipates a substantial decrease in sorghum grain production area, with QLD and NSW experiencing reductions to 385 thousand hectares and 140 thousand hectares, respectively. Consequently, the stubble available for bioenergy generation is projected to decrease from 2.4 to 1.9 million tons in QLD and from 1.1 to 0.75 million tons in NSW annually.

This reduction in available stubble translates to a proportional decrease in the fraction available for bioenergy generation. The expected energy contribution of converting all the stubble to pellet fuel for industrial heat and bioelectricity is forecasted to decrease from 111.3 to 89.2 PJ/yr in QLD and from 53.5 to 36.6 PJ/yr in NSW. Similarly, for the raw straw at the same proportion, expected declines are projected from 40.2 to 32.2 PJ/yr in QLD and 19.3 to 13.2 PJ/yr in NSW. These projections underscore the vulnerability of sorghum straw fuel pellet production to climatic variations. To mitigate this, it becomes essential to develop resilient sorghum-to-pellet conversion systems, which typically encompass pre-production (biomass growth and harvest in the field), processing (conditioning and densification), and post-production (packaging, storage, and transportation) stages [60]. Such systems would ensure adaptability to challenging climates, thereby fortifying the Australian renewable energy sector against the uncertainties posed by changing weather patterns.

4.3.2. Quality of Granular Solid Biofuel: The Ash's Chemistry is Challenging

Sorghum straw, with moisture content and energy density comparable to white wood, holds promise as a fuel pellet source in Australia (**Table 2**). However, its elevated ash content (7.9%) surpasses the acceptable range (0.7-2%) for premium-grade solid biofuels under the EN*plus*® standard, making it unsuitable for residential and commercial use [61]. This section delves into investigating sorghum straw pellet fuel quality, addressing challenges related to slagging and fouling deposits during combustion and exploring strategies to enhance ash quality.

Table 2. Technical quality of sorghum straw pellet relative to key solid fuels considered for dispatchable bioelectricity production in Australia

Indicator	Sorghum straw pellet	White wood pellet [a]	Charcoal [a]
Moisture (%)	7.9-11	7-10	1-5
Lower heating value (MJ/kg)	14.1-17.8	15-17	30-32
Volatile matter (%)	70.9-78.5	75-84	10-12
Fixed carbon (%)	18.1-18.2	15-25	85-87
Bulk density (kg/m^3)	439.5-626	550-650	180-240
Energy density (GJ/m^3)	6.2-11.15	8-11	5.4-7.7

[a] Biomass for bioenergy project–pellets factsheet [25].

Despite similarities in moisture content and energy density with white wood, sorghum straw pellets exhibit higher ash content, posing a risk of slagging and fouling during combustion in biomass conversion equipment (**Figure 6**). This excess ash could impact thermal efficiency and increase maintenance costs [20]. Ash quality in sorghum-based pellets is influenced by material handling practices, pre-pelleting treatments, and crop nutrition. Proper material handling, from harvest to storage, is crucial to avoid contamination and unintended mineral transfer [62], thereby reducing ash content. Pre-pelleting treatments like washing or soaking sorghum straw can enhance ash quality by removing or diluting minerals responsible for high ash levels and low-melting-point oxides [63].

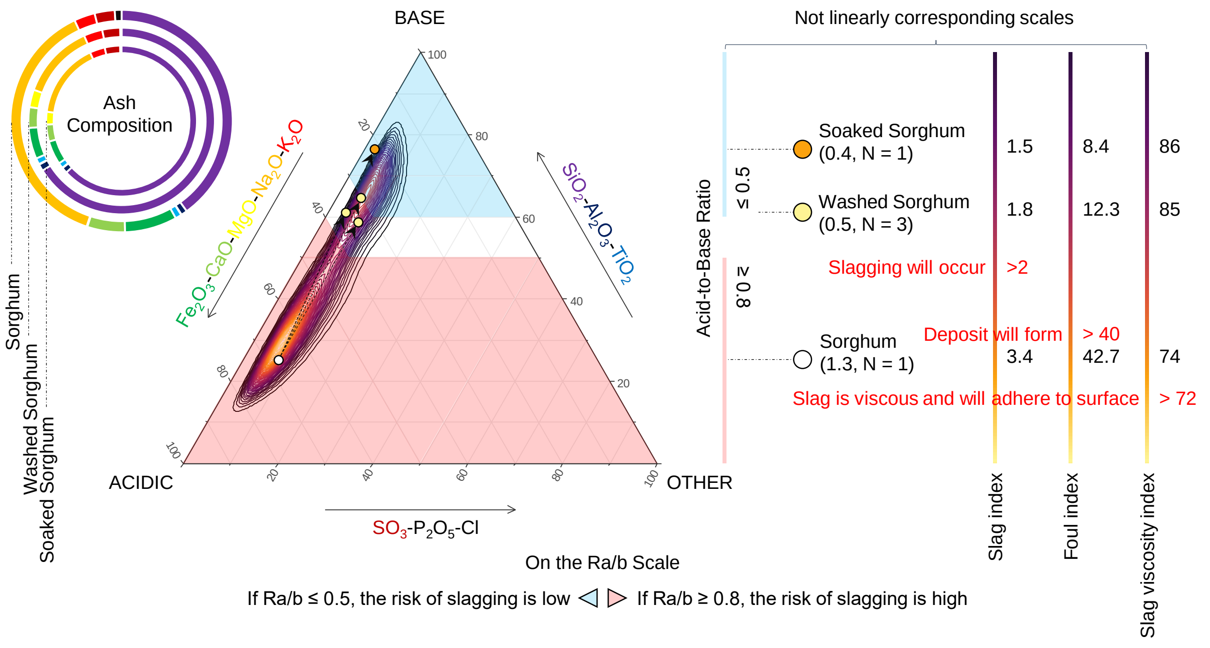

Figure 6. Ash chemistry and physical deposit formation in sorghum-based biofuel. This figure uses a ternary chart to display the composition of basic, acidic, and other ash components in sorghum-based biofuel, with colours indicating slagging risk. Scales for slag, foul, and slag viscosity indices show deposit potential. Data points highlight the effect of pre-treatment on acid-to-base ratio and deposit risk. A donut plot complements this by showing ash composition and pre-treatment effects.

Effective crop nutrition management, including a strategic silicon supply [64], plays a crucial role in optimising biomass quality by preventing the excessive accumulation of low-melting-point minerals. This is especially pertinent in scenarios where sorghum is cultivated in sodic and abandoned mining sites in Australia. Given its versatility, sorghum can thrive in diverse environments, including high salinity (sodicity) soils [65], and contribute to land reclamation on abandoned mining sites. However, these scenarios present additional challenges for the ash quality of sorghum straw pellets, as they may elevate the concentration of undesirable minerals in the biomass, particularly if sorghum acts as a phytoextractor [66].

4.3.3. Traits for Creating Resilient Sorghum-to-Pellet Conversion Systems

Sorghum is a versatile crop that thrives in water-limited environments, such as Australia's sorghum belt. However, climate change threatens its yield and quality as a renewable energy source. Key strategies to create resilient sorghum-to-pellet conversion systems include:

- Optimising flowering and water use: Sorghum yields depend on the timing of flowering and water availability. Selecting hybrids and practices that match the seasonal conditions can reduce yield risks and improve crop resilience [67].
- Modifying root system architecture: Sorghum's root system affects its water and nutrient uptake, and its adaptation to diverse environments. Altering the root angle and orientation can increase sorghum's rooting depth and access to deeper soil water, which are crucial for biomass growth, yield stability, and sustainability [68-70].
- Developing 'stay-green' and heat-tolerant varieties: Sorghum's 'stay-green' trait delays leaf senescence under drought stress and is linked to higher yields and biomass production. Sorghum's heat tolerance enables it to withstand high temperatures and extreme heat events. Developing sorghum varieties with these traits can enhance the crop's sustainability and productivity under environmental stresses [71-72].
- Engineering cell wall for silicon (Si) deposition: Si strengthens sorghum tissues, enhancing its resistance to lodging and herbivory [73]. It also alters the ash chemistry, reducing the risk of slagging and fouling during biomass combustion [74]. Engineering sorghum to have more

Si in stem tissues could improve both the field performance and the biomass quality of sorghum for bioenergy production as granular solid biofuel, without synthetic additives [75]. However, increasing Si in sorghum might also reduce lignin concentration, which affects the calorific value and energy output of biomass [64].

- Selecting for dual-purpose and perenniality: Sorghums with heights between 1.8 and 2 meters can lower the HI, leading to increased stubble. This height also potentially dilutes minerals in the biomass, reducing ash content and improving suitability for pelleting. By prioritising perenniality, the need for yearly replanting is minimised, which reduces both input costs and carbon footprint, especially in tropical regions [76].

Sorghum cultivation in Australia offers many opportunities for renewable energy generation. By focusing on traits that enhance sorghum's resilience to water and heat stress, we can ensure a more secure and productive future for sorghum-to-pellet conversion systems.

5. Sustainability Benefits of Producing Sorghum for Bioenergy

5.1. Navigating the "Food versus Fuel" Debate

The role of sorghum in Australian agriculture has evolved significantly, traditionally serving as a nutritionally competitive alternative to barley and wheat for livestock such as cattle [77], poultry [78], and pigs [79]. Responding to changing needs and opportunities, recent developments have highlighted sorghum's potential in gluten-free diets [80], particularly for individuals with celiac disease, expanding its applications from the feed to the food industry. However, this expansion has introduced a new challenge: balancing sorghum's use across the food, feed, and burgeoning fuel industries.

The ongoing "food versus fuel" debate in the bioenergy sector emphasises the importance of judiciously selecting bioenergy feedstocks to minimise impacts on food security. Despite the absence of concrete evidence linking biofuels from sugar, cereal grains, and oilseeds to feedstock price escalation in Australia, pricing dynamics significantly influence farmers' crop selection decisions. Cultivating non-food feedstocks on fertile land raises sustainability concerns, although there is a growing consensus that fuel and food production can coexist, exemplified by the use of bagasse, a sugarcane refining by-product.

Sorghum, a coarse grain, has witnessed shifts in market dynamics. Despite price decreases during drought conditions, demand from domestic and international feed grain sectors has kept prices relatively high. The complexity of the sorghum market is underscored by quality variations attributed to weather conditions during harvest, impacting poultry rations and emphasising the need for diversification to provide additional income and economic security to growers [41].

Recent studies by the ARC Centre of Excellence in Plant Cell Wall at The University of Adelaide have identified sorghum varieties with superior biofuel feedstock potential. A specific variety, rich in mixed-linear beta-D-glucans, offers enhanced stability and durability for storage and transport, facilitating bioethanol production. Non-wood pellets made from sorghum straw exhibit favourable properties for bioenergy production, surpassing standards for premium solid biofuels [45].

Additionally, this study demonstrated that non-wood pellets made from sorghum straw have a high content of holocellulose (57.5±5.2%) and lignin (20.2±3.8%), resulting in high bulk density (616.85 kg/m^3) and heating value (18.7 MJ/kg). These properties surpass the standards for premium solid biofuels under EN*plus*® (**Table 3**). Sorghum straw pellets can be utilised for bioenergy production, while the grains can be reserved for animal feed and human food.

Economic assessments by O'Hara et al. [81] highlight the cost-effectiveness of utilising surplus straw for pellet production compared to other options like syrup, bioethanol, electricity, and animal feed. Sorghum-based biomass pellets, priced similarly to coal, generate revenue through renewable energy certificates, resulting in comparable internal rates of return and net present values despite lower cogeneration capital costs. The reduction in GWP achieved through pellet production and combustion further supports its environmental benefits.

The critical debate surrounding sorghum's use in the food, feed, and fuel industries emphasises the need for a balanced and sustainable approach to crop selection and land use. Understanding sorghum's role in this debate is crucial for developing sustainable agricultural practices and fostering the growth of the bioenergy sector in Australia. The future of sorghum, like all bioenergy feedstocks, depends on our ability to navigate these complex issues effectively.

Table 3. Comparison of sorghum straw pellets and ENPlus woody biofuel standards in terms of physical and chemical properties

Indicator	Metric	Sorghum	EN*Plus*® A1	EN*Plus*® A2	EN*Plus*® B	Comparison
Diameter	mm	6.5[a]-7.8[b]	6±1, 8±1	6±1, 8±1	6±1, 8±1	**Diameter [✓] and Length [⊖]:** Sorghum pellets' diameter is within EN*plus*® standards, ensuring efficient combustion and handling. However, their length may exceed the standards, potentially affecting durability and combustion.
Length	mm	33.5[a]-44.5[b]	3.15 ≤ L ≤ 40	3.15 ≤ L ≤ 40	3.15 ≤ L ≤ 40	
Moisture	w%	10[a,b,c]	≤ 10	≤ 10	≤ 10	**Moisture [✓] and Ash [✗]:** The moisture content is at the upper limit of the EN*plus*® standards, which could reduce calorific value and pose storage challenges. The ash content exceeds the standards, which could lead to slagging and fouling in the combustion system.
Ash	w%	3.4[d]-7.9[e]	≤ 0.7	≤ 1.2	≤ 2	
Durability	w%	85.7[a]-93.5[c]	≥ 98	≥ 97.5	≥ 97.5	**Durability [✗] and Bulk Density [⊖]:** The durability of sorghum pellets falls below the EN*plus*® standards, indicating a potential risk of degradation. The bulk density may be within the standards, affecting storage and transport.
Bulk density	kg/m^3	365.2[a]-626[f]	600 ≤ BD ≤ 750	600 ≤ BD ≤ 750	600 ≤ BD ≤ 750	
Net calorific value	kWh/kg	4.4[e]-4.8[f]	≥ 4.6	≥ 4.6	≥ 4.6	**Net calorific value [✓] and Nitrogen [⊖]:** The net calorific value aligns with or exceeds the EN*plus*® standards, indicating a satisfactory energy yield. However, the nitrogen content slightly surpasses the A1 standard but is within the A2 and B ranges.
Nitrogen	w%	0.4[f]	≤ 0.3	≤ 0.5	≤ 1	
Sulphur	w%	0.1[f]	≤ 0.04	≤ 0.04	≤ 0.04	**Sulphur [✗] and Chlorine [✗]:** The sulphur and chlorine content in sorghum pellets exceeds the EN*plus*® standards, raising potential environmental and operational concerns.
Chlorine	w%	0.04[f]	≤ 0.02	≤ 0.02	≤ 0.03	
Arsenic	mg/kg	0.6[f]	≤ 1	≤ 1	≤ 1	**Heavy Metals [✗]:** The heavy metal content in sorghum pellets surpasses the EN*plus*® standards, posing potential environmental and health risks. Adherence to established standards is crucial.
Cadmium	mg/kg	3[f]	≤ 0.5	≤ 0.5	≤ 0.5	
Chromium	mg/kg	84.4[f]	≤ 10	≤ 10	≤ 10	
Copper	mg/kg	242.8[f]	≤ 10	≤ 10	≤ 10	
Lead	mg/kg	63.2[f]	≤ 10	≤ 10	≤ 10	
Mercury	mg/kg	13.6[f]	≤ 0.1	≤ 0.1	≤ 0.1	
Nickel	mg/kg	54[f]	≤ 10	≤ 10	≤ 10	
Zinc	mg/kg	609.6[f]	≤ 100	≤ 100	≤ 100	

[a] Theerarattananoon et al. [92], [b] Puig-Arnavat et al. [93], [c] Tumuluru et al. [19], [d] Garcia et al. [94], [e] Carvalho et al. [95], [f] Wiloso et al. [96].

Traffic light code: Comply [✓] and do not comply [✗], irrespective of the class; acceptable, depending on the class [⊖].

5.2. Protecting Aquatic Life: Mitigating Agricultural Runoff in Northern Australia

The Great Barrier Reef, the world’s largest coral reef system, is under threat from agricultural runoff. This runoff, originating primarily from farmlands, carries an excess of nutrients, pesticides, and sediments into the marine environment, resulting in detrimental impacts on coastal ecosystems. The sugarcane industry, spanning approximately 400 thousand hectares in the Great Barrier Reef catchment, is identified in the report as a major contributor to water pollution and the subsequent deterioration of coral health. Despite covering only 1.4% of the catchment area, the sugarcane industry contributes to 78% of the anthropogenic load of dissolved inorganic nitrogen and over 95% of the pesticide load [82], limiting the expansion of the sugarcane industry for food or potential bioenergy crop production.

Riparian buffers, which are vegetated strips along watercourses, serve multiple functions, such as filtering pollutants, stabilising banks, and providing habitats for wildlife [83]. The establishment of these zones using rainforests or grasses like sugarcane has demonstrated promising results in reducing nitrogen runoff in the Wet Tropics and Burry Mary catchments. This success is attributed to their enhanced fertiliser management and ground cover, minimising environmental impacts [82]. However, sorghum could provide a more resilient option with its robust root system architecture [84].

Specifically, the cultivation of sorghum, a suitable bioenergy crop for tropical and subtropical regions, on marginal lands has been proposed. Sorghum boasts high biomass yield, low water and nutrient requirements, and high tolerance to drought and salinity [85]. Notably, sorghum exhibits a higher NUE, producing more biomass per unit of nitrogen input than other crops, including sugarcane and switchgrass [86]. This reduces the risk of nitrogen leaching and runoff from the soil, especially when its footprint is comparable with that of the activity being replaced or improved.

5.3 Sorghum: A Green Solution for Rehabilitating Abandoned Mining Sites

Australia hosts over 80,000 inactive and unrehabilitated mining sites, posing environmental, public health, and safety risks [87]. These sites often contain soils contaminated with heavy metals like cadmium and zinc, which can pollute waterways and damage ecosystems. Most of these sites are west of the Great Dividing Range, minimising runoff impact on the Great Barrier Reef. Cultivating sorghum on these sites could restore them and produce bioenergy. Idemitsu Kosan Co., Ltd., a Japanese company operating at the Ensham Coal Mine, is cultivating sorghum for fuel pellet production, including use in steel works and foundries. There is significant research interest in screening high lignin sorghum varieties and management practices such as planting density, fertiliser, and irrigation application [88].

However, solid biofuel derived from biomass grown on contaminated lands like mining sites must meet globally recognised standards. The risk of unsafe and inefficient combustion due to poor biomass quality should not be overlooked. While sorghum fuel pellets meet some of the EN*plus*® standards, they fall short in areas like ash content and heavy metal content, resulting in a lower overall quality rating. A strategic approach is crucial to minimise mining impacts and realise sorghum's dual potential for phytoremediation and energy biomass production. The Queensland Government's Risk and Prioritization Framework for Abandoned Mine Management and Remediation offers valuable guidance in this context [89].

6. Conclusion

This review investigates the potential of sorghum stubble as a biomass feedstock for non-wood fuel pellets in Australia. An estimated 3.6 million tonnes of stubble could be harvested annually for bioenergy, potentially fulfilling nearly half of Australia's bioelectricity potential. The review analyses the availability and characteristics of sorghum stubble for pellet production, highlighting its low moisture content and high energy density. However, it also acknowledges challenges such as climate variability and ash-related issues during combustion. Strategies to enhance the biomass quality and performance of sorghum stubble pellets are proposed, including breeding for taller crops and higher silicon content in the stem tissues.

The review emphasises the potential of sorghum stubble pellets in renewable energy generation, their role in Australia's energy transition, and benefits for the sorghum industry, ecological conservation, and social initiatives. It recognises ongoing research in torrefaction technology that could further enhance the potential of sorghum biomass pellets as a clean and renewable energy source, positioning it as a sustainable alternative to conventional fossil fuels and other Australian biomass and waste-to-energy materials.

However, the review acknowledges limitations, including the scarcity of Australian literature on sorghum pelleting and the absence of region-specific harvest indices in the 2023 NVT sorghum harvest report. These factors may affect the accuracy of the estimation of the cereal stubble available for bioenergy generation, leading to potential over or underestimations of the bioenergy potential of sorghum stubble in regions of QLD, NSW, and WA. These limitations underscore the need for further research and data collection in this field to ensure the sustainable and efficient use of sorghum stubble for bioenergy generation in Australia.

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CRediT authorship contribution statement

Bruno Rafael: Conceptualisation, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualisation. Damian Hine and Ian Godwin: Writing – review & editing, Visualisation. Sudhir Yadav: Supervision, Conceptualisation, Methodology, Writing – review & editing, Visualisation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI in Scientific Writing

During the preparation of this work the authors utilised Microsoft Copilot, an AI-assisted technology, to improve the overall readability of the manuscript. After utilising this tool/service, the authors reviewed and edited the content as necessary. As a result, they take full responsibility for the accuracy, integrity, and scientific rigor of the publication.

Data availability

Data will be made available on request.

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