

Effect of Physical and Chemical Treatment on the Characteristics of Wheat Straw as Fuel for Energy Applications

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The use of wheat straw as a renewable energy source is essential from both energy production and environmental points of view. It has a great energy potential that can be generated either by combustion or anaerobic digestion. However, there are some limitations during its conversion to energy in both techniques. Therefore, the current study investigated the effect of physical and chemical treatments on the characteristics of wheat straw as fuel for energy applications. Water washing of wheat straw and mixing with KOH solution were applied for physical and chemical treatments. Physical, chemical, and thermal characteristics of wheat straw were investigated before and after the treatments. It was found that the wheat straw has high carbon (44.8%) and volatile contents (87.1%), making it an excellent source for energy production. The physical treatment showed a positive impact on reducing the ash content (by 14.9%) and undesirable compounds, such as K and Cl, which were reduced by 46.4% and 57.0%, respectively. Moreover, it reduced sintering formation through combustion. In contrast, the chemical treatment resulted in 9.3% lignin removal and destroyed the complex lignocellulosic structure, thereby increasing the cellulose accessibility and enhancing the anaerobic digestion process. Therefore, the applied treatments showed attractive options to solve problems related to straw energy generation.

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INTRODUCTION

Fossil fuel consumption and depletion for energy generation as well as the increase of climate change and global warming worldwide are great motivations to use renewable energy sources (Said *et al.* 2020; Abdel Daiem and Said 2024) as a sustainable option. Biomass is a clean and renewable source of energy that can include different wastes from crops, such as wheat, which is considered one of the most abundant crops worldwide (Cazaudehore *et al.* 2023). The use of wheat straw as a renewable source of energy can avoid open field burning, save energy, and protect the environment (Alrowais *et al.* 2023). Wheat straw has a great potential of energy that can be generated by direct techniques, such

as combustion, or indirect techniques such as anaerobic digestion process (Abdel Daiem and Said 2022).

In general, straw has a low bulk density and is difficult to handle, transport, store, and utilize in its original form. This issue can be overcome by densification techniques such as pelletizing or briquetting. The densified straw can be easily handled and can reduce the costs of transportation, handling and storage; moreover, the densification process also provides potential storage for off-season utilization (Eling *et al.* 2024)

However, there are some limitations for both techniques during conversion of wheat straw to energy. In a combustion technique, the thermal conversion suffers from some technical and operating problems because of sintering and slag formation that are related to the high ash content and alkali compounds in the straw ash (Siddiqi *et al.* 2022). This can be solved by straw treatment before combustion process. Physical treatment methods, such as water washing of straw, have been demonstrated as a feasible and economic option to reduce the straw ash content and undesirable compounds related to these problems (Wu *et al.* 2019).

Although the combustion technique has the advantage of high energy conversion efficiency compared to other techniques, anaerobic digestion is considered an economic and eco-friendly technique (Abdel Daiem and Said 2022; Alrowais *et al.* 2023). However, the anaerobic digestion of wheat straw is limited due to its complex structure, where cellulose and hemicelluloses are tightly bound to lignin, which can prevent microbial degradation during fermentation process (Elsayed *et al.* 2022). Thus, straw treatment before anaerobic digestion is essential to enhance the accessibility to cellulose and hemicelluloses, as well as increase degradation and biogas production from digestion process (Alrowais *et al.* 2023).

Chemical treatment is found to be efficient in lignin breakdown and increases cellulose accessibility (Mirmohamadsadeghi *et al.* 2021; Ouahabi *et al.* 2021; Alrowais *et al.* 2024a, 2024b). Potassium hydroxide (KOH) pretreatment is considered one of the most effective chemical methods that can improve digestibility of biomass (Memon and Memon 2020). Moreover, the mechanical pretreatment that includes milling or grinding of straw represents the most traditional treatment technologies, which can modify the straw biomass particle size (Samar *et al.* 2021). The particle size reduction can decrease cellulose crystallinity, increase the specific surface area, enhance bio-accessibility of degradable substrate, and facilitate the fermentation process (Tan *et al.* 2021). This approach has a positive effect on biogas production, as found in previous study (Victorin *et al.* 2020). Therefore, it can be combined with chemical treatment technologies to achieve an efficient treatment (Alrowais *et al.* 2023).

The studies related to physical or chemical treatment of wheat straw are limited. So, the main aim of this study was to compare the effect of physical and chemical treatments with respect to improving the physical, chemical, and thermal characteristics of wheat straw, especially for using it as a fuel for combustion and anaerobic digestion processes. Washing straw with tap water to remove undesirable compounds was used as a simple method for physical pretreatment of straw for the combustion process. Chemical treatment using KOH agent was applied to improve straw digestibility characteristics for anaerobic digestion process. Moreover, the electric energy potential from wheat straw through combustion and anaerobic digestion process was estimated in Saudi Arabia. Reduced carbon emissions due to the use of wheat straw as a fossil fuel substitute for energy generation was also evaluated.

EXPERIMENTAL

Material and Methods

Wheat straw was collected from a field in Al-Jouf region, Saudi Arabia. It was then shredded to a size smaller than 1 mm. Chemical treatment was completed using KOH as a chemical agent. The KOH solution of 0.6 M was mixed with the shredded straw then heated at 90 °C for 2 h in an air oven. After treatment, the samples were washed well (5 g of sample was stirred moderately and continuously in 1L of distilled water from 1 to 2 min; this was repeated to obtain a neutral pH). The washed samples were filtered, dried in an air oven at 105 °C to obtain a constant weight, and then stored in plastic bags for subsequent analysis.

For the physical treatment, the straw was chopped to around 1.0 to 2 cm, washed with tap water, and then dried in an air oven at 105 °C to obtain a constant weight. The dried samples were shredded to a size smaller than 1 mm and saved in plastic bags for subsequent analysis. Table 1 presents methods and analysis used for measuring the different parameters of the current study.

Table 1. Analytical Methods Used in the Present Study

Parameter	Method
Total solids (TS), Total volatile solids (TVS), Total nitrogen (N), Total carbon (C)	Rice <i>et al.</i> (2012)
Ash content	Muffle furnace at 550 °C for 5 h
Element analysis	Spectrophotometer (DRB200 Reactor 1 Block 9 ×1 6 mm / 2 × 20 mm)
Scanning electron microscopy (SEM)	JEOL JEM-850 operating at 25 kV
Lignocellulosic composition	Said (2016); Sluiter <i>et al.</i> (2008)
High heating value (HHV)	Bomb-calorimeter (LECO AC-500, Germany)
pH	pH Meter, Ultrameter 6PII FCE W/OUT PKUU KIT pocket-sized
Thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG)	Shimadzu TGA-50H thermo analyzer (30 to 1000 °C, 10 °C /min heating rate, 100 mL/min flow rate (air atmosphere))

The potential electric energy that can be obtained from wheat straw produced in the Kingdom of Saudi Arabia will be estimated in this study. Around 800,000 tons of wheat crop are produced annually with 117,647 ha area cultivated in the kingdom (MEWA 2022). The generated wheat straw can be evaluated based on the residue-to-crop product ratio (1.25) according to Eq. 1 (Molina-Guerrero *et al.* 2020). The energy potential of wheat straw can be estimated using Eq. 2. The LHV of wheat straw (14.63 MJ/kg) was calculated based on the experimental value of HHV (dry basis) following the method used in Montero *et al.* (2016). The potential electric energy that can be generated from wheat straw through combustion and anaerobic digestion processes can be calculated based on combustion power plant combined with a steam turbine cycle and anaerobic digestion plant combined with a steam turbine power plant with an electric efficiency of 30% and 35%, respectively (Jiang *et al.* 2019). The energy conversion factor for biogas production varies from 0.38 to 0.88. The energy generation from each process was computed using Eq. 3,

$$WS = WP \times RR \quad (1)$$

$$EP_{WS} = WS \times LHV_{WS} \quad (2)$$

$$EG_{WS} = EP_{WS} \times PE \times ECF \quad (3)$$

where WS is wheat straw (kg), WP is wheat production (kg), RR is residue to product ratio, EP_{WS} is energy potential of wheat straw (MJ), LHV_{WS} is lower heating value of wheat straw (MJ/kg), EG_{WS} is electricity generation from wheat straw (MJ), PE is power-generation efficiency (%), and ECF is energy conversion factor.

RESULTS AND DISCUSSION

Wheat straw is a bio-waste of low moisture content and high content of solids (92.5%) with a high carbon content (44.8%). Table 2 indicates the chemical characteristics of untreated straw (UTS), and physically treated straw (PTS), and chemically treated straw (CTS) materials. The UTS may contain a higher content of some elements compared to PTS. This may be attributed to contamination of straw with some soil elements (Wu *et al.* 2019). Through the straw washing process, these elements can be dissolved in water and their content decreases (Singhal *et al.* 2021). As a result, the content of the main straw constituents increases as a percentage of the whole straw. Physical treatment by water washing showed a decrease in contents of N, P, K, Cl, S, Zn, Na, and Fe with a ratio of 9.72%, 4.71%, 46.43%, 57.01%, 19.14%, 11.36%, 39.34%, and 7.5%, respectively. Respectively, the contents of C, H, Si, and Ca increased by 3.13%, 2.42%, 17.97%, and 8.94% compared to those of the untreated straw. Similar results are found in previous studies as well (Wu *et al.* 2019; Singhal *et al.* 2021, 2023; Bhatnagar *et al.* 2022).

In the chemical treatment, some elements including C, H, N, P, K, Si, Cl, Na, and S were decreased by 5.76%, 17.74%, 12.50%, 52.94%, 16.78%, 61.78%, 32.79% and 6.38%, respectively. The reduction in the contents of these elements is attributed to the effect of chemical treatment and washing process after chemical treatment, which can cause removal in some elements that can be dissolved in washing water (Rani *et al.* 2022; Siddiqi *et al.* 2022). In consequence, the contents in increase of the other elements including Ca, Zn, and Fe have been observed, with a ratio of 17.9%, 24.6%, and 40.0%, which is similar to results of previous studies (Al-Da'asen *et al.* 2022; Rani *et al.* 2022; Siddiqi *et al.* 2022). Furthermore, there are some elements, including Cu, Ni, and Mn, which have not been detected in the untreated straw, but were detected in small percentages with physical and chemical treatments.

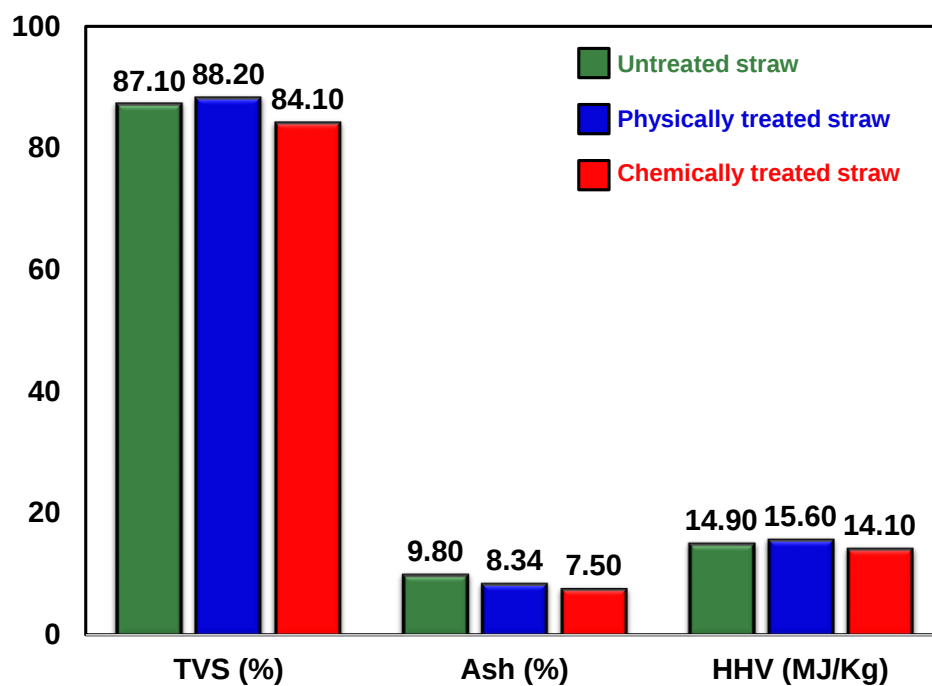
Fig. 1 shows HHV, TVS, and ash content of the untreated and treated straw. As observed, the straw had high volatiles content (87.10%) that were increased to 88.2% by the physical treatment as a result of washing the contaminants attached to the straw surface during harvesting (Wu *et al.* 2019). Otherwise, the volatiles content decreased from chemical treatment to reach 84.1%. This is because of the effect of chemical treatment on the degradation of some ingredients of hemicellulose that causes a decrease in volatile matter of the straw (Tan *et al.* 2021).

Moreover, ash content of untreated straw (9.8%) was decreased by physical and chemical treatments to reach 8.34% and 7.50%, respectively. The reduction in ash content was due to chemical treatment effect and washing of the straw, which extracts large amounts of alkali metals, Cl, S, P, and other elements that are present on the straw surface from soil contamination (Wu *et al.* 2019; Singhal *et al.* 2021).

Table 2. Chemical Characteristics of Untreated Straw, Physically Treated, and Chemically Treated Straw Materials

Parameters (% dry matter)	Untreated straw	Physically treated straw	Chemically treated straw
C	44.8	46.2	42.2
H	6.2	6.4	5.10
N	0.72	0.65	0.63
P	1.7	1.62	0.80
K	4.2	2.25	2.40
Si	14.3	16.9	11.9
Ca	12.3	13.4	14.5
Cl	3.1	1.35	1.20
S	2.4	1.90	2.20
Zn	2.2	1.95	2.74
Fe	0.80	0.74	1.12
Na	0.61	0.37	0.41
Cu	ND	0.01	0.15
Ni	ND	0.07	0.11
Mn	ND	0.12	0.16

ND Not detected

**Fig. 1.** Higher heating value (HHV), Total volatile solids (TVS), and ash contents of the untreated and treated straw

The physical treatment improved the HHV by 4.7% and is correlated to ash reduction due to washing process. However, the chemical treatment showed a reduction in HHV by 5.4% compared to the untreated straw. This decline may be attributed to dissolution of hydrocarbons by KOH during the treatment process, where C and H contents directly contribute to the heating values (Siddiqi *et al.* 2022). This is confirmed by the results of elemental analysis, where C and H content reduction was recorded by the chemical treatment of straw.

Fig. 2 shows the lignocellulosic composition of untreated and treated straw materials. Through washing, the surface elements of straw that were present due to soil contamination during harvesting were removed. Physical treatment indicated increment in lignocellulosic contents (cellulose, hemicellulose, and lignin contents increased by 1.38%, 1.13%, and 1.99%, respectively). In contrast, chemical pretreatment can cause destruction of the hemi-lignin structure, removal of lignin, and solubilization of hemicellulose (Tan *et al.* 2021). The chemical treatment of straw showed a reduction in hemicellulose and lignin contents at 2.26% and 9.27%, respectively, compared to untreated straw. Similar results were found in previous studies (Memon and Memon 2020; Rani *et al.* 2022). However, an increment in cellulose content of 4.85% was recorded because of reduction in lignin and hemicellulose contents, as explained by previous studies (Sabeeh *et al.* 2020; Tan *et al.* 2020; Samar *et al.* 2021).

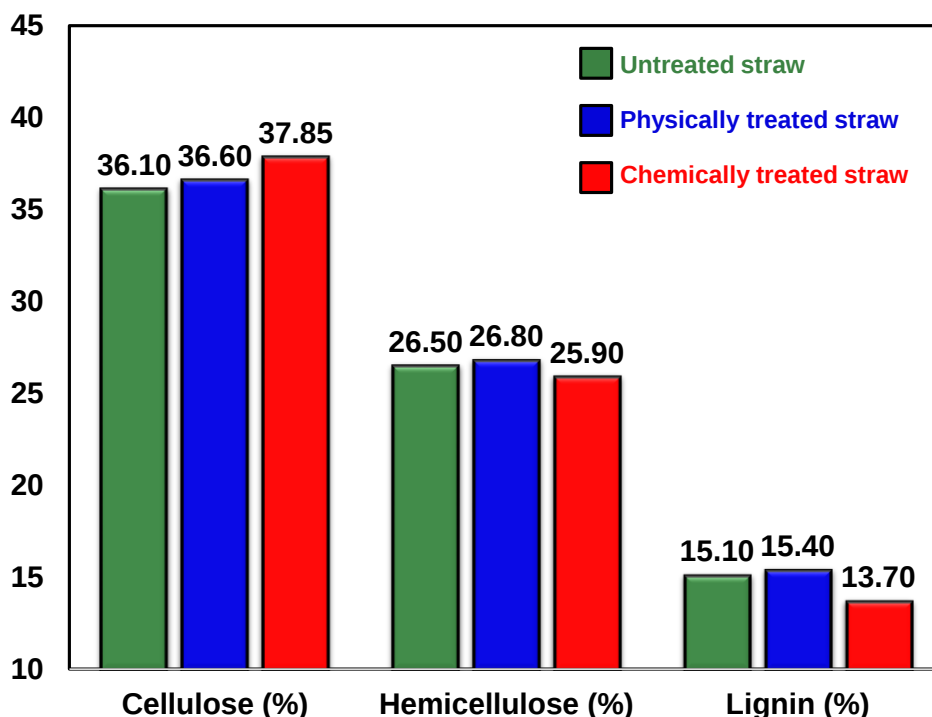


Fig. 2. Lignocellulosic composition for untreated and treated straws

The SEM inspection of the untreated and treated straw samples is illustrated in Fig. 3. As shown in Fig. 3a, the surface structure of the UTS is compact, flat, and smooth. The physical treatment by washing did not affect the internal or surface structure of straw, as indicated in Fig. 3b. Similar detection was observed in other studies (Wu *et al.* 2019; Singhal *et al.* 2021). Otherwise, Fig. 3c illustrates that the chemical treatment resulted in the destruction of the straw surface, destroying the complex lignocellulosic structure,

removing some external fibers as well as partial lignin removal (as supported by results of Fig. 2), and in turn, exposing the internal surface (see Fig. 3c). This can enhance cellulose accessibility to microorganisms and improve biodegradation and fermentation in anaerobic digestion process. These findings are consistent with the results of other studies (Mirmohamadsadeghi *et al.* 2021; Ouahabi *et al.* 2021; Tan *et al.* 2021). Some elements, such as K, S, and Cl, were observed in high amounts in UTS, while they were detected in small amounts in the treated straw materials because of the effect of washing process.

The TGA and DTG curves for untreated and treated straw samples are illustrated in Fig. 4. The TGA showed mass loss and DTG indicated three peaks with three stages. The first stage below 100 °C and indicated moisture removal. The second stage represented degradation of cellulose and hemicellulose components (200 to 300 °C). The third stage began after 300 °C and was attributed to lignin decomposition. After 500 °C, mass loss was negligible, and a continuous straight line was detected because of ash residue after complete combustion of the straw. Similar results were found by Marin-Batista *et al.* (2021) and Siddiqi *et al.* (2022).

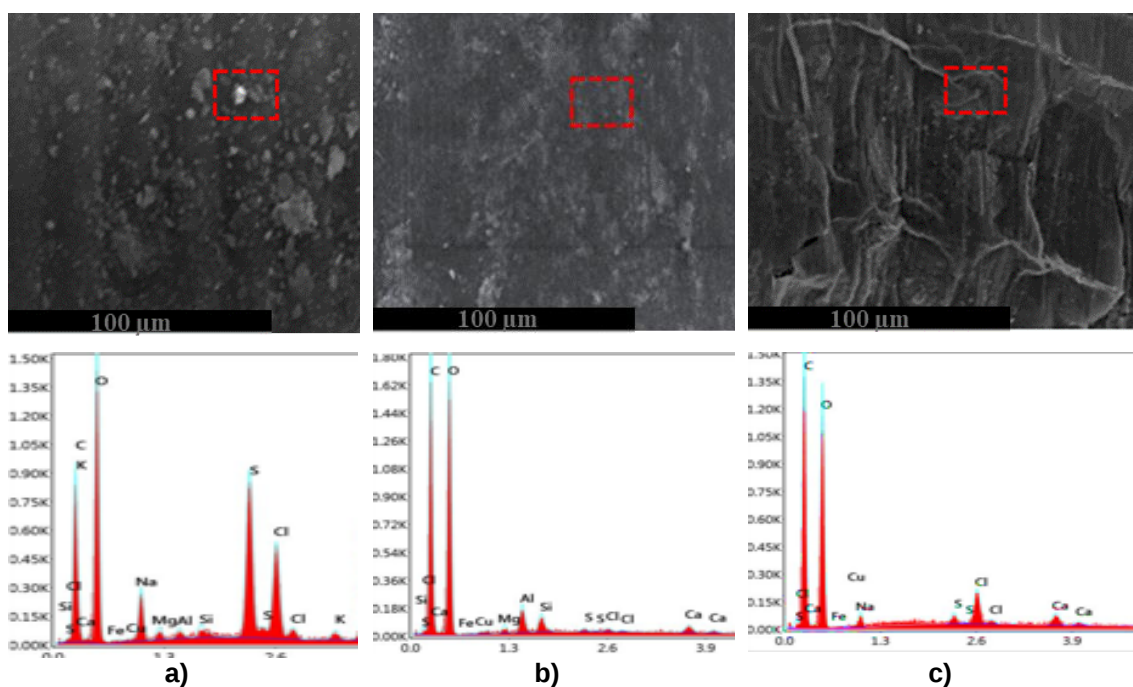


Fig. 3. SEM and spot analyses of straw a) untreated, b) physically treated, and c) chemically treated

The TGA curves showed lower ash residues for the treated samples compared to the UTS. Furthermore, CTS recorded the lowest ash residue in the TGA profile and indicated the highest peak in the DTG curve. Therefore, it showed the highest cellulose and lowest lignin contents compared to other samples. These findings confirm lignocellulosic composition of the untreated and treated straws, as illustrated in Fig. 2. The results are consistent with other studies (Marin-Batista *et al.* 2021; Bhatnagar *et al.* 2022; Siddiqi *et al.* 2022).

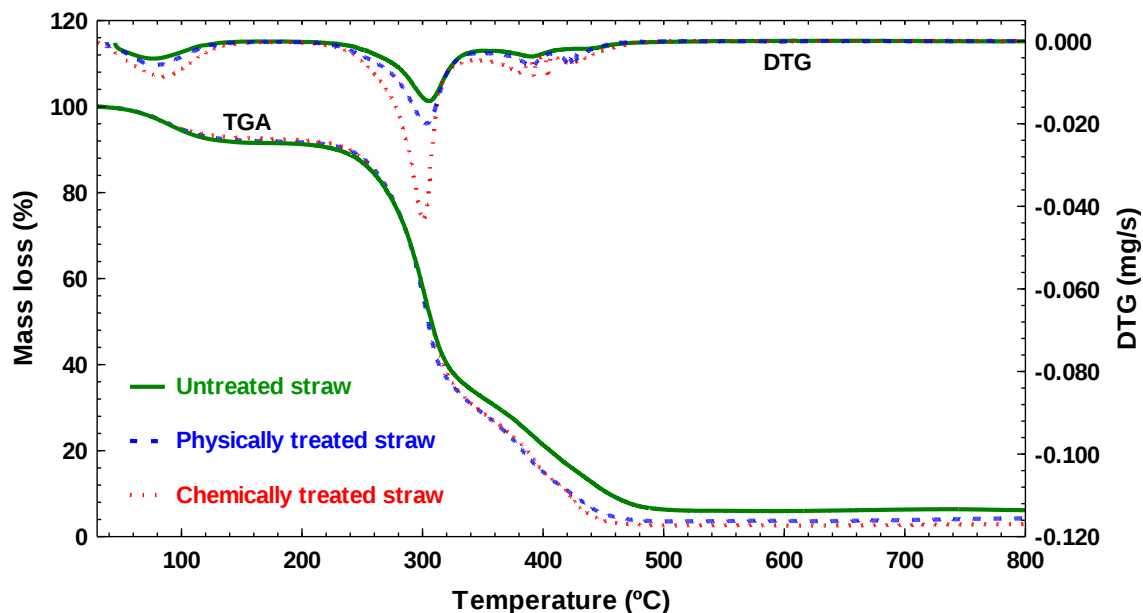


Fig. 4. TGA and DTG thermograms of untreated and treated straw samples

Samples of UTS and PTS were tested for the combustion process. Fig. 5 shows photos of shredded straw samples before and after combustion in the muffle furnace. The combusted UTS samples showed strong sintering when the samples were heated to 1000 °C (Fig. 5b). Otherwise, sintering formation was not detected for the combusted PTS samples at the same temperature (Fig. 5c). This is attributed to the reduction of undesirable compounds by washing the straw (Singhal *et al.* 2021). Therefore, physical treatment by straw washing resulted in considerable changes in inorganic composition, decreased the risk of sintering formation, and improved the combustion behavior of the straw. This agrees with the findings of Wu *et al.* (2019).

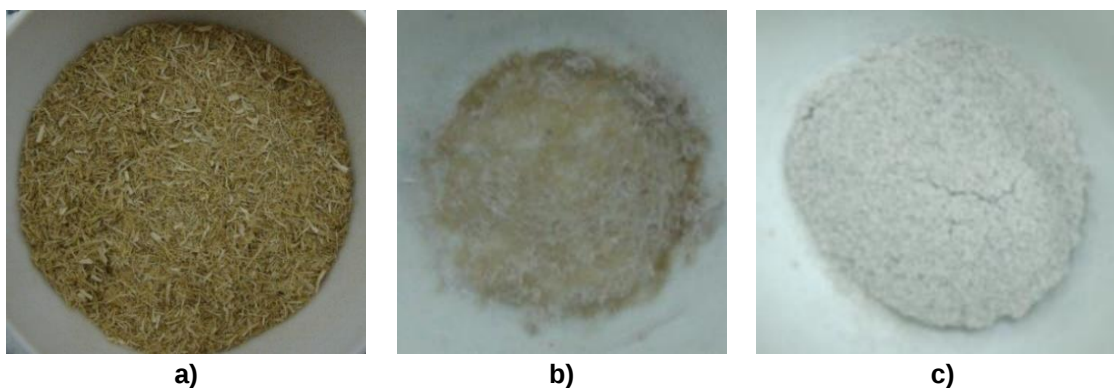


Fig. 5. Pictures of straw a) untreated, b) combusted untreated, and c) combusted physically treated

Table 3 presents wheat straw production, energy potential, electric energy potential, and carbon emissions avoidance in the case of using wheat straw as a fuel instead of fossil fuels in Saudi Arabia. Around one million tons of wheat straw are produced annually in Saudi Arabia. The total energy potential estimated from this amount reached 14.6 PJ/year. The potential electricity generation from combustion and anaerobic digestion plants was

estimated at 1.22 and 0.84 TWh/year, respectively. These estimations represent approximate values, and the process can be scaled up to take the energy requirements for the treatments into consideration and calculate the actual energy that can be obtained from treated wheat straw. Moreover, the drying step can be carried out by leaving the straw in the sun outdoors due to the presence of an arid climate, and this can save energy requirements. In a previous study, the sun drying of rice straw after rain full decreased its moisture content to 20% (Sekine *et al.* 2014). Another study showed a reduction in moisture content of bagasse to from 50% to 24% by solar drying (Ali *et al.* 2022).

On the other hand, the use of wheat straw as a fuel substituting fossil fuel can mitigate environmental pollution. The potential for avoiding carbon emissions resulting from the displacement of fossil fuels has been estimated based on the carbon avoidance factor per unit of power generation (0.62 kg CO₂/kWh) (Tan *et al.* 2014). The total carbon emissions avoided by generating electricity from wheat straw substituting fossil fuel through combustion and anaerobic digestion plants could reach 0.76 and 0.52 million tons of CO₂/year, respectively. Thus, wheat straw utilization for energy generation can reduce the waste volume and fossil fuel consumption and mitigate CO₂ emissions that contribute to global warming and climate change.

Table 3. Potential Electric Energy and Carbon Emissions Avoidance (CEA)

Data	Value
WS (tons/year)	1000000
EP _{ws} (PJ/year)	14.63
EG _{ws} (combustion) (TWh/year)	1.22
EG _{ws} (anaerobic digestion) (TWh/year)	0.84
CEA (combustion) (million tons of CO ₂ /year)	0.76
CEA (anaerobic digestion) (million tons of CO ₂ /year)	0.52

CONCLUSIONS

This study aimed to investigate the effect of physical and chemical treatments of wheat straw on its characteristics as fuel for energy applications.

1. The wheat straw has high carbon with around 45% and volatile contents (87%), making it an excellent source for energy production. The physical treatment reduced the ash content by 15% and some undesirable compounds, including K and Cl by 46% and 57%, respectively. Furthermore, the ash sintering problem was reduced during combustion.
2. The chemical treatment resulted in 9.27% lignin removal and destroyed the complex lignocellulosic structure, so it can enhance cellulose accessibility and anaerobic digestion performance. Thus, both of treatments showed a positive impact on reduction problems related to energy generation from wheat straw.
3. Around, one million tons of wheat straw was produced annually in Saudi Arabia with estimated energy potential of 14.6 PJ/year. The potential electricity generation through combustion and anaerobic digestion plants was estimated at 1.22 and 0.84 TWh/year, respectively. The total carbon emissions avoided by generating electricity from wheat straw substituting fossil fuel through combustion and anaerobic digestion plants could

reach 0.76 and 0.52 million tons of CO₂ /year, respectively. Thus, wheat straw utilization for energy generation can reduce the waste volume and fossil fuel consumption and mitigate CO₂ emissions that contribute to global warming and climate change.

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