Analysis of Energy and Greenhouse Gas Emissions of Rice Straw to Energy Chain in Egypt

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Rice straw as a source of energy could substitute for fossil fuels and reduce greenhouse gas (GHG) emissions. Thus, the aim of this paper was to analyze the energy and GHG emissions of rice straw to the energy chain in Egypt. The analysis was performed starting from paddy production, straw collection and transportation, and energy generation for two scenarios: power plant and anaerobic digestion plant. The results showed that the paddy production and transportation stage represented the highest contribution of the total energy consumption and GHG emissions for the two scenarios, respectively. The energy potential was estimated with 4193 GWh electricity and 25,647 × 10^6 MJ of biogas energy. It was also found that use of rice straw as an energy source could reduce the use of fossil fuel and mitigate air pollution from direct burning of rice straw by 3 Mt CO_2-eq of GHG emissions.

Keywords: Rice straw; Energy; GHG emissions; Electricity; Biogas

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INTRODUCTION

Widespread and massive consumption of fossil fuels has led to rapid economic growth in advanced industrial societies, but it has also increased carbon dioxide (CO_2) in the atmosphere and consequently caused global warming and climate change (Bilgen *et al.* 2008). In consequence, alternative energy sources, such as renewable energies, are an opportunity to replace and/or subsidize fossil fuels and obtain the safest, most cost-efficient, and most practical energy (Bilgen *et al.* 2008; Demirbas *et al.* 2009). Currently, renewable energy supplies 17% of the world's primary energy, counting traditional biomass that represents 9%, nevertheless, it is projected to double the share of renewable energy in the global final energy consumption by 2030 (Demirbas *et al.* 2009).

Rice straw as a biomass source is produced in great amounts, and it represents the largest unutilized crop residue in Egypt (Said *et al.* 2013b). Field burning is the major practice for removing rice straw, but it results in air pollution and consequently affects public health (Sarkar *et al.* 2012). However, rice straw has a high energy potential and thus can become a source of alternative energy that substitutes fossil energy for reducing GHG emissions as well as avoid the local pollution problems from open burning (Said *et al.* 2013a, 2014). Today, densified rice straw can be easily handled and transported to recover its energy (Said *et al.* 2015). Energy from rice straw can be recovered directly in the form of heat through a combustion process, or it can be converted to a valuable energy product through indirect techniques such as anaerobic digestion (AD) (Said *et al.* 2013a; Abdel Daiem *et al.* 2018; Ahmed *et al.* 2019).

Some scientific articles have studied the life cycle assessment of rice straw-based power generation and analyzed energy and environmental aspects related to the use of rice straw as an energy source in different countries (Singh *et al.* 2010; Delivand *et al.* 2011; Shafie *et al.* 2013, 2014; Soam *et al.* 2017). Due to the low number of studies and lack of information about rice straw utilization for energy generation in Egypt, the main objective of this paper was to analyze the energy and GHG emissions of rice straw preparation stages for energy generation in Egypt. The analysis was performed starting from paddy production, straw collection, straw transportation, and energy generation.

EXPERIMENTAL

Materials

Data collection

Data of paddy production and cultivated areas was collected from the Central Agency for Public Mobilization and Statistics (CAPMS 2018). The different rice producer governates in Egypt are Port Said, Damiietta, Dakahliya, Sharkia, Qalyoubia, Kafr Elsheikh, Gharbia, Behera, Ismailia, Beni suef, and Fayoum, as illustrated in Fig. 1. Paddy production, cultivated areas in these governates are indicated in Table 1. As indicated in the table, Dakahlia, Kafr Elsheikh, Sharkia, Behera, and Gharbia are the largest rice cultivation areas. These governates contribute 97.41% of the Egyptian rice production. The amount of rice straw production was derived according to Shafie *et al.* (2014), using the value of straw to grain ratio (0.75). As indicated in the table, approximately 97.41% of the total rice straw production was generated in the six major rice producer governates as mentioned before with respect to paddy production.

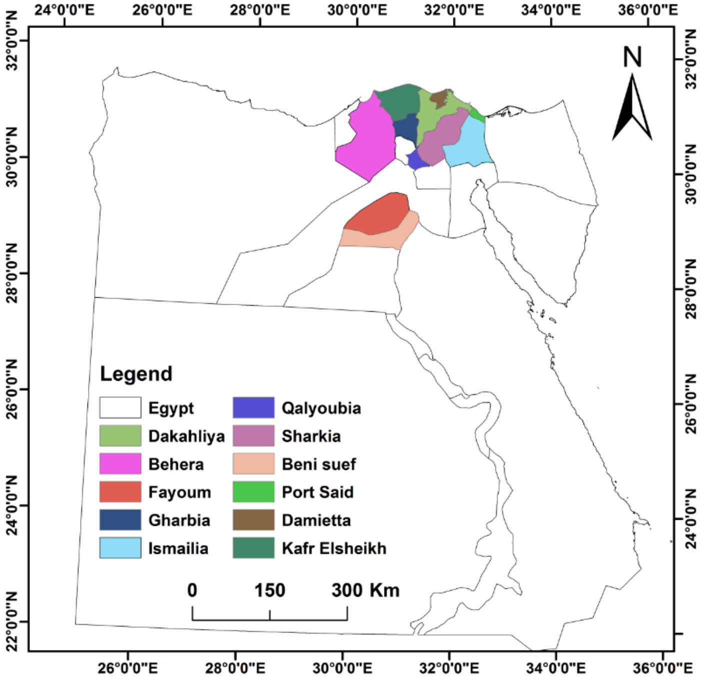

Fig. 1. An overall map of paddy production governates in Egypt

Table 1. Paddy Production, Cultivated Area, and Straw Production for the Different Governates in Egypt in 2015 (CAPMS 2018)

Governate	Paddy Production (ton)	Cultivated Area (ha)	Rice Straw Production (ton)	Total Straw Production (%)
Dakahliya	1686328.00	159877.62	1264746.00	35.01
Kafr Elsheikh	953647.00	104577.48	715235.25	19.80
Sharkia	869009.00	92871.24	651756.75	18.04
Behera	622582.00	68272.68	466936.50	12.93
Gharbia	378686.00	45572.52	284014.50	7.86
Damiietta	181364.00	24651.48	136023.00	3.77
Port Said	73612.00	8833.44	55209.00	1.53
Qalyoubia	33816.00	3816.96	25362.00	0.70
Ismailia	13183.00	1538.04	9887.25	0.27
Beni suef	2789.00	278.88	2091.75	0.06
Fayoum	1368.00	164.22	1026.00	0.03
Total	4816384.00	510454.56	3612288.00	100.00

Methods

The analysis of straw to energy chain included straw preparation; starting from paddy production, straw collection and transportation, and finally energy generation from two scenarios: power plant and AD plant, as illustrated in Fig. 2. Energy consumption and GHG emissions emitted through those processes were investigated according to inventory data displayed in Table 2. The energy consumption of straw collection included all machinery using baling technique and considered the diesel consumption in machinery (Shafie *et al.* 2014). Transportation from farm to power plant included two steps, where straw is first transported to the collection center with a tractor trolley, then transported to the power plants with a truck (Bakker 2011; Soam *et al.* 2017). For the AD process, the transportation was considered from farm to the collection center only where the straw can be directed easily to the plant to produce biogas, therefore, rural people could use the biogas for cooking (Singh *et al.* 2014; Soam *et al.* 2017).

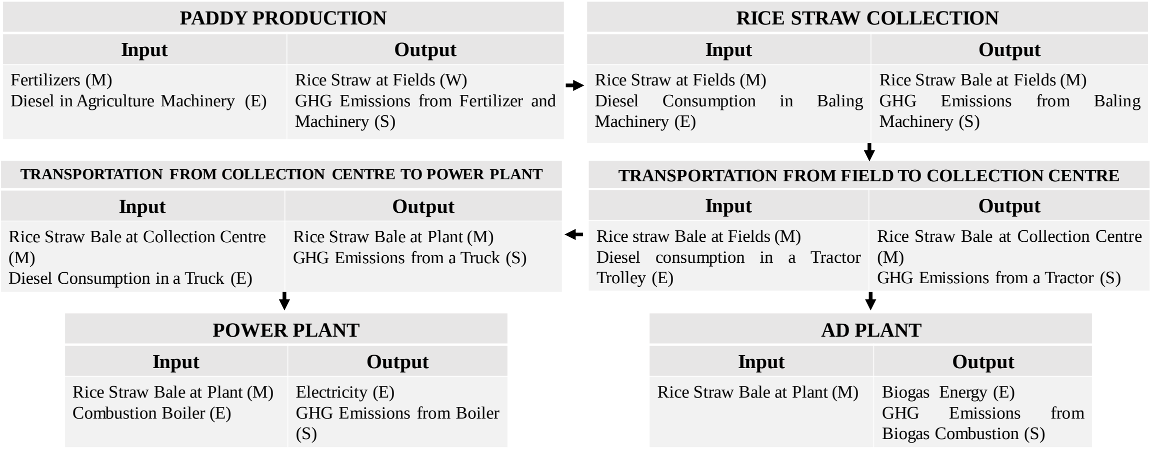

Fig. 2. System boundaries for rice straw-energy generation
Note: Material (M), Energy (E), Waste (W), and Emission (S)

The analysis quantified equivalent CO_2 emissions of the three primary GHG: CO_2, methane (CH_4), and nitrous oxide gases (NO_X) (Delivand *et al.* 2011; Shafie *et al.* 2013).

The GHG emissions from straw collection were computed considering diesel consumption (Bakker and Poppens 2011). Transport emissions are expressed in grams CO_2-eq emitted for every ton moved over one kilometer (g CO_2-eq per ton.Km), considering loaded and unloaded travel distances in kilometers and rice straw yield in tons (Bakker 2011). Biogenic emissions of CO_2 from the power plant were considered zero because the amount of CO_2 produced during combustion is utilized during photosynthesis while growing crops (Shafie *et al.* 2014). However, CO_2-eq straw fuel emissions could be estimated respecting CH_4 and NO_X gases according to Delivand *et al.* (2011), Soam *et al.* (2017), and Shafie *et al.* (2014). In contrast, CO_2 emissions from biogas combustion are biogenic and hence considered not applicable. Therefore, CH_4 and NO_X gases have been taken in consideration (Soam *et al.* 2017).

Table 2. Inventory Data Used for Energy Consumption and GHG Emission Calculations

Parameter	Value	References
Energy Consumption for Paddy Production	12225.97 MJ/ ha	Shafie *et al.* 2014
Energy Unit of Diesel	38.19 MJ/L	El Shimi and Moustafa 2018
Diesel Consumption for Paddy Production	7.00 L/ha	Shafie *et al.* 2014
Trolley Capacity	1.50 ton	Soam *et al.* 2017
Trolley Diesel Consumption (Loaded)	4.50 Km/L	Soam *et al.* 2017
Trolley Diesel Consumption (Unloaded)	5.50 Km/L	Soam *et al.* 2017
Truck Capacity	20 Bales	Soam *et al.* 2017
Truck Diesel Consumption (Loaded)	5.50 Km/L	Soam *et al.* 2017
Truck Diesel Consumption (Unloaded)	6.50 Km/L	Soam *et al.* 2017
Average Mass of Straw Bales	20.00 Kg	Soam *et al.* 2017
Transport Distance from Field to Collection Center	10.00 Km	Bakker 2011 Soam *et al.* 2017
Transport Distance from Collection Center to Power Plant	50.00 Km	Bakker 2011 Soam *et al.* 2017
GHG Emissions from Paddy Collection	1.20 Kg CO_2-eq/Kg paddy rice	Farag *et al.* 2013
GHG Emissions from Straw Collection	83.80 g CO_2-eq/MJ	Bakker and Poppens 2011
GHG Emissions from Transportation	221.00 g CO_2-eq/ton.Km	Bakker 2011
GHG Emissions from Boiler	0.001 Kg of (NO_X + CH_4)/kWh	Soam *et al.* 2017 Shafie *et al.* 2014
GHG Emissions from Biogas Combustion	0.081 kg of (NO_X + CH_4)/GJ	Soam *et al.* 2017

A power plant uses a combustion boiler with steam turbine for electricity generation. Straw characteristics are critical factors influencing the operation and maintenance of plants (Soam *et al.* 2017). The straw characteristics were used in determining lower heating value (LHV) in MJ/kg, which is used in determining electricity output power of straw (E) in KWh. The LHV and E were calculated according to Eq. 1 and 2, respectively (Gadde *et al.* 2009), where straw characteristics were taken according to Said *et al.* (2013a) as follows: moisture content (MC, 7.18%); carbon (C, 39.01%); hydrogen (H, 6.59%); nitrogen (N, 0.64%); oxygen (O, 53.32%), and sulfur (S, 0.009%). The estimate LHV is 13.82 MJ/Kg, *W* is the amount of straw in ton and the conversion efficiency of the plant (CE) was taken as approximately 30%. Equations 1 and 2 are as follows:

$$LHV = 34.8\, C + 93.9\, H + 10.5\, S + 6.3\, N - 10.8\, O - 2.5\, MC \tag{1}$$

$$E = W \times LHV \times CE \tag{2}$$

In the AD process, the plant consists of one stage operating at 30 to 40 °C, where straw is mixed with water and cattle dung to reach desired solid content of 10%. The biogas system was assumed to be a fixed dome, 2 m^3 household type, and the process operated in continuous feeding mode for 350 days/year operating cycle, and with 10 years of operational life (Singh *et al.* 2014; Soam *et al.* 2017). The energy production from the AD plant was estimated according to Börjesson and Berglund (2007) and Soam *et al.* (2017), where one ton of rice straw produces 7.1 GJ energy from biogas.

RESULTS AND DISCUSSION

Energy consumption of paddy production and straw collection for the six major governates and other governates are illustrated in Table 3. The Dakahliya governate had the highest energy consumption for both paddy production and straw collection, accounting for 31.3% of total energy consumption. Meanwhile, energy consumption of paddy production was higher than straw collection due to the high energy consumed in the farming stages due to the consumption of fertilizer and agriculture machinery activities (Farag *et al.* 2013). Kafr Elsheikh recorded the second governate for energy consumption followed by Sharkia, representing 20.5% and 18.2% of the total, respectively. The annual total energy consumption for all governates reached to 6,241 × 10^6 MJ and 137 × 10^6 MJ for paddy production and straw collection, respectively. The energy consumption of paddy production and straw collection for one kg of rice straw are 1.73 MJ and 0.038 MJ, which are lower than 2.52 MJ and 0.11 MJ estimated by Shafie *et al.* (2014), respectively.

Table 3. Energy Consumption (10^6 MJ) for the Different Governates at Different Stages

Governate	Paddy Production	Straw Collection	Transportation	
			Power Plant	AD Plant
Dakahliya	1954.66	42.74	2026.21	129.45
Kafr Elsheikh	1278.56	27.96	1145.86	73.20
Sharkia	1135.44	24.83	1044.16	66.71
Behera	834.70	18.25	748.07	47.79
Gharbia	557.17	12.18	455.01	29.07
Damiietta	301.39	6.59	217.92	13.92
Others	178.88	3.91	149.92	9.58
Total	6240.80	136.46	5787.14	369.71

Transportation energy for the energy consumption-based power plant was higher than AD due to the high transportation distance. The highest transportation energy consumption was found in Dakahliya, as it had the highest straw yield. Transportation energy for the energy consumption-based power plant and AD plant is indicated in Table 3. As demonstrated in the table, transportation energy consumption-based power plant for Dakahliya accounted to 2026.21 × 10^6 MJ/ year, while its value was 129.45 × 10^6 MJ/year for the AD-base plant. Dakahliya, Kafr Elsheikh, Sharkia, Behera, Gharbia, and Damietta accounted approximately 35.01%, 19.80%, 18.04%, 12.93%, 7.86%, and 2.59% of the total, respectively. The annual total transportation energy of the consumption-based power plant and AD plant reached to approximately 5,788 × 10^6 MJ and 370 × 10^6 MJ, respectively.

Considering all stages of rice straw preparation, the total energy consumption-based power plant and AD accounted to 12,160 × 10^6 MJ/year and 6,750 × 10^6 MJ/year, respectively. For the power plant, the highest contribution to the total energy consumption was from paddy production (51.3%), followed by transportation (47.6%), and straw collection (1.12%). In case of AD, the transportation energy consumption represented only 5.48% of the total followed by straw collection (2.02%) and the highest energy consumption was from paddy production (92.5%). The high energy consumption in paddy production stage can be attributed to the high energy consumed in farming stages due to consumption of fertilizers and agriculture machinery use as found and described by Shafie *et al.* (2014).

Energy production from rice straw for the different governates power plants and AD plant is illustrated in Fig. 3a and b, respectively. As indicated in the figure, Dakahliya had the maximum annual energy production, accounting for 35.0% of the total energy production. The annual electricity output from rice straw fuel-based power plant in Dakahliya was 1,468 GWh, while energy from biogas generated from AD plant was 8,980 × 10^6 MJ. The annual total energy obtained for all governates was 4,193 GWh electricity and 25650 × 10^6 MJ of biogas energy for straw fuel-based power plant and AD plant, respectively. Thus, the electricity production from one ton of rice straw was 1165 KWh, which was higher than 938 KWh found by Shafie *et al.* (2014) and lower than 1367 KWh estimated by Soam *et al.* (2017). The variation in energy obtained by these studies may be attributed to the different characteristics of the used rice straw and according to the power plant efficiency (Soam *et al.* 2017).

The GHG emissions of rice straw-based energy generation begins with paddy production and continues to energy generation. The CO_2 gases represent a high percentage of GHG emissions (Shafie *et al.* 2014). Only as an exception, the paddy production process has a great advantage in relation to the global warming impact, due to the absorption of carbon through photosynthesis (Abdelhady *et al.* 2014; Shafie *et al.* 2014). Table 4 shows GHG emissions (CO_2-eq) for paddy production and straw collection. As shown in the table, the highest annual GHG emissions emitted from paddy production and straw collection were found in Dakahliya with values of 2,050 t CO_2-eq and 3,582 t CO_2-eq, accounting for 35.0% and 31.3% of the total, respectively. Meanwhile, the total GHG emissions emitted from paddy production and straw collection for all governates were 5,857 t CO_2-eq/ year and 11,435 t CO_2-eq/year, respectively. The obtained CO_2-eq from straw collection was approximately 0.003 Kg CO_2-eq/Kg straw, which is lower than 0.012 Kg CO_2-eq/Kg straw calculated by Bakker and Poppens (2011). Furthermore, The GHG emissions from both paddy production and straw collection were equivalent to 0.01 Kg CO_2-eq/Kg straw, which is lower than 0.10 Kg CO_2-eq/Kg straw estimated by Shafie *et al.* (2014). The difference in emissions is likely due to differences between studies in farming location, type, allocation method, energy, and emission coefficients (Miller and Kumar 2013).

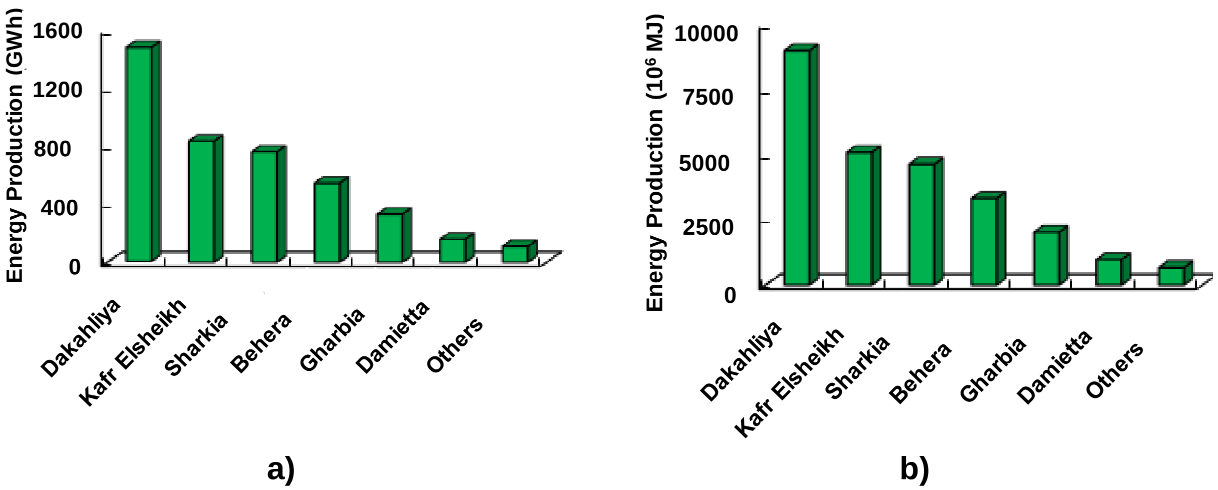

Fig. 3. Energy production for the different governates from rice straw-based a) power plant and b) AD plant

Table 4. GHG Emission (t CO_2-eq) for the Different Governates at Different Stages

Governate	Paddy Production	Straw Collection	Transportation	
			Power Plant	AD Plant
Dakahliya	2050.57	3581.62	33541.06	5590.18
Kafr Elsheikh	1159.63	2342.77	18968.04	3161.34
Sharkia	1056.71	2080.53	17284.59	2880.76
Behera	757.06	1529.46	12383.16	2063.86
Gharbia	460.48	1020.93	7532.06	1255.34
Damiietta	220.54	552.25	3607.33	601.22
Others	151.72	327.78	2481.64	413.61
Total	5856.73	11435.33	95797.88	15966.32

Transportation distances play a major role in GHG emissions. Increases in the transportation distance from the collection center to power plant contribute to increased GHG emissions, as detected by Shafie *et al.* (2014). Table 4 includes GHG emissions emitted from the transportation of rice straw fuel-based power plant and AD plant, respectively. As can be seen in the table, a remarkable increase in emissions emitted from transportation to power plant comparing AD plant was detected, as found by Soam *et al.* (2017). Dakahliya as the highest governate in GHG emissions emitted from transportation, has annual values of approximately 33,540 t CO_2-eq and 5,590 t CO_2-eq for the power plant and AD plant, respectively. Meanwhile, the annual total GHG emissions emitted from transportation to power plant and AD plant for all governates were 95,800 t CO_2-eq and 15,970 t CO_2-eq, respectively.

The GHG emitted from plants includes emissions from the combustion boiler of the rice straw power plant and combustion of biogas generated from the AD process. As mentioned before, CO_2 emissions from the straw-based power plant and biogas combustion are biogenic and considered zero; therefore, GHG emissions included CH_4 and NO_X gases. Figure 4 illustrates the GHG emissions generated according to boiler and biogas combustion. As indicated in Fig. 4, GHG emission was higher for the combustion boiler compared to biogas combustion, similar to Soam *et al.* (2016). This indicated that the straw fuel-based AD process has more environmental benefits than the power plant (Soam *et al.*

2016). The annual GHG emitted in Dakahliya, as the greatest values among different governates, reached to 1,468 t CO_2-eq and 727 t CO_2-eq from the power plant and AD plant, respectively. Meanwhile, the total GHG emissions emitted from the combustion boiler of the rice straw power plant and combustion of biogas generated from the AD process for all governates accounted to 4,190 t CO_2-eq/year and 2,080 t CO_2-eq/year, respectively. The difference in emissions for the two plants arises due to different processing technologies and the displaced product (Soam *et al.* 2016).

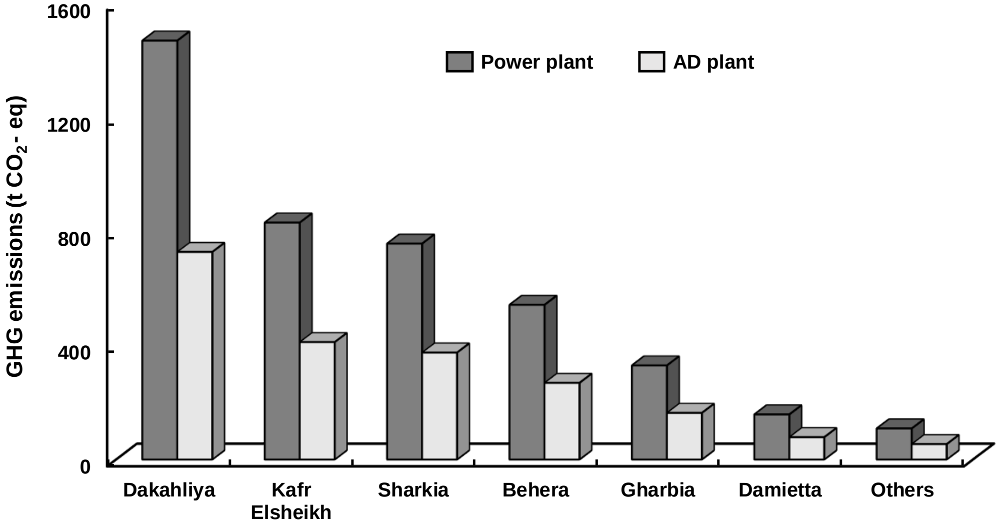

Fig. 4. GHG emissions from energy generation processes

Based on the results of the current study, the total annual GHG emissions generated from rice straw-based power plant are 117,280 t CO_2-eq, which are higher than 35,340 t CO_2-eq from the AD plant. Figures 5a and b indicate the GHG emission contribution of the different stages for rice straw fuel-based power plant and the AD plant. For the power plant, transportation had the highest emissions, accounting for 81.7% of the total emissions, followed by straw collection and paddy production. Similar results were found by Soam *et al.* (2017) and Shafie *et al.* (2014), where they found that the highest contribution to the total GHG emissions was from straw transportation with 92% and 57.5%, respectively. Meanwhile, combustion boilers of the power plant had the lowest emissions among the different stages. Although transportation emission represented the highest contribution among the different stages-based AD plant, its contribution percentage (45.2%) was lower than that (81.7%) from the power plant. For the straw fuel-based AD, the second highest contribution was for straw collection followed by paddy production, while biogas combustion emission had the lowest percentage (5.88%), as can be seen in the figure.

According to the obtained results, the annual air pollution of 3.2 Mt CO_2-eq from the direct burning of rice straw (Farag *et al.* 2013) could be mitigated by using rice straw for electricity generation and biogas energy source to 0.12 Mt CO_2-eq and 0.035 Mt CO_2-eq, respectively. Therefore, it is expected to have a GHG emission reduction of approximately 3 Mt CO_2-eq per annual country emissions from non-open field burning and using rice straw as an energy source. This reduction represents approximately 0.94% reduction of the total annual country's GHG emissions (Nakhla *et al.* 2013). Similar results were found by Delivand *et al.* (2011) who expected to have a GHG emission reduction of approximately 2 to 3.5 Mt per year, which is equivalent to approximately 1 to 1.13% reduction to the total annual Thailand's GHG emissions. Additionally, Shafie *et al.* (2014) found that the power generation of rice straw, if applied, can reduce the GHG emission up to 1% of total GHG emissions in Malaysia. These small percentages of reduction will become more attractive in the future as these countries strive to reduce their carbon emissions. According to Delivand *et al.* (2011), 0.368 t CO_2-eq/t dry straw and 0.683 t CO_2-eq/t dry straw could be avoided if straw is used instead of natural gas or coal fuel in the power generation sectors. In consequence, 1.24 Mt CO_2-eq and 2.29 Mt CO_2-eq could be mitigated annually by substituting the natural gas and coal fuels with rice straw for power generation, respectively. Moreover, 152 m^3 natural gas/t dry straw or 0.285 t coal/t dry straw could be saved (Delivand *et al.* 2011). As a result, an annual amount of 510 × 10^6 m^3 natural gas and 957,400 t coal could be saved. Based on the country, fossil fuel consumption for electricity generation of 230 ton of oil equivalent (toe)/GWh (Abdelhady *et al.* 2014), the straw fuel power plant could be able to reduce the use of fossil fuel by an amount of 964,400 t/year. Thus, the utilization of rice straw for energy generation not only removes the rice straw from field without open burning, but also saves GHG emissions that can contribute to climate change, acidification, and eutrophication, among other environmental problems, as well as it would contribute to savings on the fossil fuel consumptions (Delivand *et al.* 2011; Shafie *et al.* 2014).

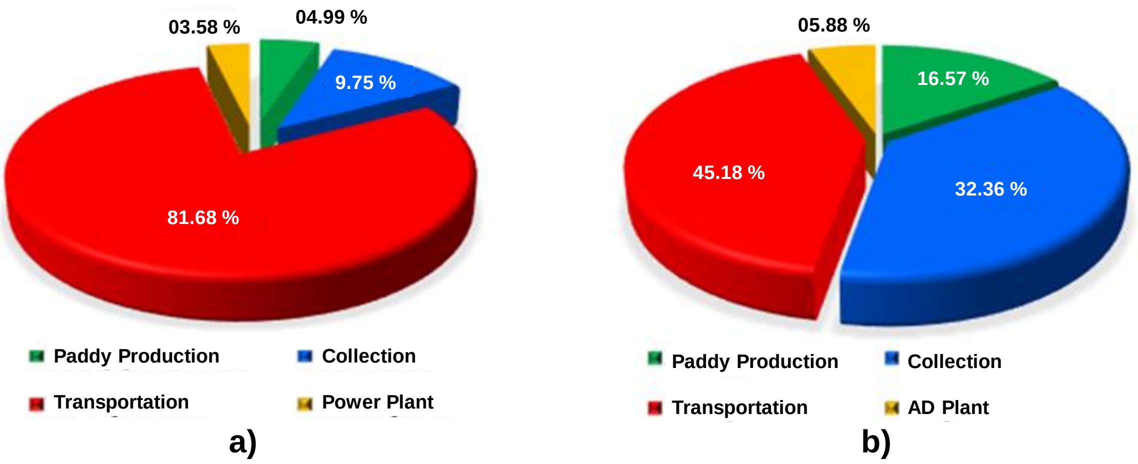

Fig. 5. GHG contribution of the different stages to the total emissions of rice straw fuel-based a) power plant and b) AD plant

CONCLUSIONS

1. The paddy production and transportation stage represented the highest contribution of the total energy consumption and greenhouse gas (GHG) emissions, respectively.
2. The annual total energy obtained amounted to 4193 GWh electricity and 25,650 × 10^6 MJ of biogas energy from straw fuel-based power plant and AD plant, respectively.
3. Air pollution from direct burning of rice straw could be mitigated by 3 Mt CO_2-eq of GHG emissions by using rice straw as an energy source.

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