Prognosis of access to biomass residue resources in rural areas to provide energy for villagers

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Abstract

The potential evaluation of available biowaste was carried out for 95 villages of Gorgan in this study. The resources studied were wastes resulting from agricultural activities, including farming, horticulture, and livestock, as well as rural waste and wastewater. A coefficient was used to access the resources by filling a questionnaire, interviewing with experts and the use of the fuzzy analytic hierarchy process in order to have a theoretical estimation of resources closer to reality. This coefficient was determined based on the five factors including the suitability of warehousing, ease of transportation, quality of collection mechanism, access to production areas and no collection losses. Then, the information was geo-referenced in geographic information system. It was found that the total potential of the villages was 1,191,022 GJ, most of which were related to agricultural (9,87,986 GJ) and horticulture (94,416 GJ) waste, respectively. Regarding the per capita waste generation and the limiting factor of distance from natural gas transmission lines, southern parts of the province could be among the priority villages for biofuels development.

Keywords Biomass · Biowaste · Residual biomass · Bioenergy · Rural residue · Potentiometric · FAHP

1 Introduction

Bioenergy production has received a considerable attention during recent years. Consequently, some concerns have been raised regarding this rapid growth which include the change in ecosystem, an increase in food prices and resource constraints. Utilizing the residual biomass is an approach to decrease the negative influences of biomass energy production [1]. All liquid and solid wastes which are indirectly or directly the outcome of human activities are called residual biomass and, in the matter of production, are considered as waste. These residuals are produced in a variety of areas, including industrial and agricultural production units, food stores, commercial and residential areas and other different places [2]. Regarding the economic and environmental aspects, residual biomass is available. Nevertheless, evaluation

of its potential applications when added to other supply chains is necessary. The lack of concentration, which leads to a difficult collection and transportation, is one of the major limitations of the biomass resources in terms of producing energy from these materials. Hence, an accurate estimation of their potential and utilization for producing energy in susceptible areas are necessary [3]. Furthermore, it is critical to manage the biomass resources sustainably, and although they are abundant and geographically distributed widely, they should be utilized with permission.

The purpose of the present study is to estimate the residual biomass resources' potential for renewable energy production in Gorgan county, Iran. The energy resources in this region for the residential sector are fossil fuels, including liquefied petroleum gas, gasoline, natural gas and kerosene. The natural gas is provided for the residents

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by the national pipeline, and other sources of energy are hard to provide.

In this respect, after determination of the magnitude of residual biomass, qualitative criteria were identified for each resource access. The paired comparison method and the fuzzy analytical hierarchy process (FAHP) method were used to determine the weight of each factor which were considered as the coefficients of the corresponding resource. Lastly, the geographical information system (GIS) was used to analyze the waste resources, and rural areas' status was determined regarding the waste materials' potential and accessibility to the regular energy carriers of the region.

1.1 Case study

Gorgan, in the south part of Golestan, is located in the southeast of the Caspian Sea and northeastern of Iran. There are three areas in this region, including foothills, sub-humid and plain. The north and south of the city have semi-humid and mountainous climate, respectively. Arable land in Gorgan is about 63,157 km² which is approximately 39% of the total land areas. Figure 1 shows the dispersion map of the villages and the corresponding lands. The rural population is 118,478 people which accounts for about 23% of the total population of Gorgan. The dispersion map for the rural population of the region is presented in Fig. 2 [4, 5]. In the present study, statistical average data for 95 villages, which were provided in 2018, were used

Fig. 1 Land use in study area

Fig. 2 Population dispersion (People)

as the study regions for which the rural biowaste potential is estimated. Just like many other cities in Iran, Gorgan uses natural gas transmission pipelines to provide thermal energy to the rural and urban areas. Having 19.6 million Iranian households who use natural gas service line from the late 2017, this is the major residential energy supply in Iran [6]. Since many villages are located far from the major pipeline, they do not have access to the fuel. The energy resources for these rural areas are usually being provided by old methods which have problems regarding the health issues and energy supply.

2 Methodology

The residual biomass resources are categorized based on the purpose of the present study, as listed in Table 1. Because of difficulty in collecting the waste and the low production and proportion of the wastes, other agricultural products and other residual biomass sources are neglected. Agricultural and rural waste data were provided and classified from the Gorgan Annual Census Data since 2018. Data were gathered through interviews with the Rural Council for villages with no available information.

First, accessibility to the resources was determined so the estimated and actual values will be more consistent.

Table 1 Biomass classification in villages of Gorgan

Biomass resources	Description
Farming	Grain (wheat, barley, soybean, rice) vegetable (potato and tomato) residue
Horticulture	Fruit residue Tree residue
Rural Waste	Household
Wastewater	Household
Livestock	Cow and calf Sheep, ewe and goat Horse Chicken

The access coefficients were regarded as a factor for the utilization of resources. This method was determined based on the principal and technology of organic waste utilization [2] and the status of the residual biomass accessibility, cultivation, crop type, production dispersion, mechanization of operation and other similar factors. Five qualitative parameters, including ease of

Fig. 3 Tree diagram of resource accessibility **Fig. 4** The fuzzy triangular numbers equal to qualitative number**Table 2** Linguistic variable and their fuzzy equivalent

	The triangulated fuzzy number	Quantitative number
Very low	(0,0,0.25)	0.1
Low	(0.25,0.25,0.25)	0.3
Medium	(0.5,0.25,0.25)	0.5
High	(0.75,0.25,0.25)	0.7
Very high	(1,0.25,0)	0.9

Table 3 The fundamental scale of AHP

Definition	Score
Equal importance	1
Weak importance of one over another	3
Essential or strong importance	5
Very strong and demonstrated	7
Absolute importance	9
Intermediate values between adjacent scale values	2,4,6,8

biomass collection, ease of transportation, storage suitability, access to production areas and quality of collection mechanism, were chosen for determination of the factor of accessibility to the resources by interviewing nine researchers and experts. The criteria's weights were determined by the fuzzy analytical hierarchy process (FAHP) method. Figure 3 presents the tree diagram of the network analysis process.

Based on the aforementioned five parameters, 15 experts who were selected by Snowball sampling technique designed and weighted the pair comparison questionnaire. The snowball sampling technique is a consecutive purposive sampling method which is applicable in

Fig. 5 Graphical abstract of the study methodology **Table 4** Scoring table for the accessibility coefficient (weighted values)

	Storage suitability	Ease of transportation	Quality of collection mechanism	Access to production areas	Ease of collecting biomass	Importance degree
Storage suitability	1	0.5	0.33	0.25	0.33	0.072
Ease of transportation	2	1	0.5	0.25	0.5	0.111
Quality of collection mechanism	3	2	1	0.5	2	0.244
Access to production areas	4	4	2	1	2	0.388
Ease of collecting biomass	3	2	0.5	0.5	1	0.184
Inconsistency = 0.02						

Table 5 Quantitative values of qualitative criteria

	Storage suitability	Ease of transportation	Quality of collection mechanism	Access to production areas	Ease of collecting biomass
Farm	0.7	0.5	0.9	0.3	0.5
Horticulture	0.7	0.5	0.3	0.5	0.7
Rural Waste	0.3	0.5	0.5	0.7	0.5
Wastewater	0.1	0.3	0.3	0.5	0.7
Livestock	0.3	0.3	0.5	0.9	0.7

multi-criteria decision making where the researcher asks the expert, who provides data, to introduce other experts [7].

Triangular fuzzy number (TFN) method was used in the present study to evaluate the residual biomass source accessibility. This method was chosen because of the nature and number of the options. In this method, a

Table 6 Weights of each factor for each of the sources

Accessibility factor	Importance degree	Resource	Qualitative criteria	Weight
Storage suitability	0.072	Farm	0.7	0.050
		Horticulture	0.7	0.050
		Rural Waste	0.3	0.022
		Wastewater	0.1	0.007
		Livestock	0.3	0.022
Ease of transportation	0.111	Farm	0.5	0.056
		Horticulture	0.5	0.056
		Rural Waste	0.5	0.056
		Wastewater	0.3	0.033
		Livestock	0.3	0.033
Quality of collection mechanism	0.244	Farm	0.7	0.171
		Horticulture	0.3	0.072
		Rural Waste	0.5	0.122
		Wastewater	0.3	0.072
		Livestock	0.5	0.122
Access to production areas	0.388	Farm	0.3	0.116
		Horticulture	0.5	0.194
		Rural Waste	0.7	0.272
		Wastewater	0.5	0.194
		Livestock	0.9	0.349
Ease of collecting biomass	0.184	Farm	0.5	0.092
		Horticulture	0.7	0.129
		Rural Waste	0.5	0.092
		Wastewater	0.7	0.129
		Livestock	0.7	0.129

triangular fuzzy number with the form of (m, a, b) represents a qualitative option, where m , a and b are the mean, left and right tolerances, respectively $[(0,0,0.25 = \text{very low}), (0.25,0.25,0.25 = \text{low}), (0.5,0.25,0.25 = \text{medium}), (0.75,0.25,0.25 = \text{high}), (1,0.25,0 = \text{very high})]$. The TFN corresponding to each one of the qualitative numbers is shown in Fig. 4.

The Chen–Hwang method is used to convert a triangular fuzzy number to a definite value [8]. Maximum and minimum functions as follows have to be defined firstly for converting normal fuzzy numbers to definite amounts:

$$\mu_{\text{Max}}(x) = \begin{cases} x & 0 \leq x \leq 1 \\ 0 & \end{cases} \quad (1)$$

$$\mu_{\text{min}}(x) = \begin{cases} 1 - x & 0 \leq x \leq 1 \\ 0 & \end{cases} \quad (2)$$

The maximum and minimum values create the right and left tolerances for the fuzzy number. These values are the membership degree of the fuzzy number $(\mu(x))$ at the intersection points where the right and left tolerances are shown as $(\mu_L(x))$ and $(\mu_R(x))$. Given the

triangular fuzzy numbers (m, a, b) , the definite values of the left and right tolerance, and quantitative number, can be obtained from the following equations:

$$\mu_R(x) = 1 - \frac{1}{1+b}(1-m) \quad (3)$$

$$\mu_L(x) = 1 - \frac{1}{1+a}(m) \quad (4)$$

$$\mu_T = \frac{m+b}{2(1+b)} + \frac{m}{2(1+a)} \quad (5)$$

where μ_T is a number which is equal to the TFN shown by m , a and b . m is the average value, a is left tolerance value, and b is right tolerance value as listed in Table 2.

The analysis hierarchy process (AHP) was selected by the expert choice software and used to obtain the weight of the sub-criteria and criteria. The pair-wise comparison matrix was used to measure the significance of each of the criteria compared to the others. Let a_{ij} be the element lying in the i th row and j th column of the

Table 7 Overall desirable accessibility of each source

Resource	Accessibility factor	Weight
Farm	Storage suitability	0.050
	Ease of transportation	0.056
	Quality of collection mechanism	0.171
	Access to production areas	0.116
	Ease of collecting biomass	0.092
Horticulture	Storage suitability	0.050
	Ease of transportation	0.056
	Quality of collection mechanism	0.072
	Access to production areas	0.194
	Ease of collecting biomass	0.129
Rural waste	Storage suitability	0.022
	Ease of transportation	0.056
	Quality of collection mechanism	0.122
	Access to production areas	0.272
	Ease of collecting biomass	0.092
Wastewater	Storage suitability	0.007
	Ease of transportation	0.033
	Quality of collection mechanism	0.072
	Access to production areas	0.194
	Ease of collecting biomass	0.129
Livestock	Storage suitability	0.022
	Ease of transportation	0.033
	Quality of collection mechanism	0.122
	Access to production areas	0.349
	Ease of collecting biomass	0.129

matrix, and the following formula is used to fill the lower diagonal:

$$a_{ji} = \frac{1}{a_{ij}} \quad (6)$$

Lastly, the relative and total weights were calculated for each factor and the access coefficient was determined for each resource. The scale range of 1–9 by Thomas Saaty was used to weight the factors, as listed in Table 3 [9].

Determination of the residual biomass potential was done based on its heating value for co-equilibrating the resources values. The instructions of Washington State University Biomass Inventory [10–12] and Bioenergy Assessment and University of Freiburg Biomass Energy Europe Project were used for estimation [13, 14]. The agricultural and rural wastes were categorized into five classes, including household waste, farming and horticulture waste, wastewater, livestock and poultry manure and agricultural residue, after the data of 95 villages were collected for the region. Since they are the major crops of the region, barley, wheat, rice and rapeseed were considered for grain waste, while tomato and potato

waste were considered for vegetable waste. Two categories of wastes were considered for horticulture products, including waste of the leaves and crop loses and wastes of the branches which correspond to the annual tree trimming. The products of this region include peach, pear, apple, olive, citrus, cherry and plum. The amount of horticulture and agricultural biomass is theoretically collected per year. This is done using Eqs. 7 and 8 in form of Mega joules per unit area where the higher heating value (HHV) is used to convert biomass into energy.

$$EA_j = \sum_{i=1}^n (CA_{i,j} \times AP_{i,j} \times PtR_{i,j} \times Av_{i,j} \times HHV_i) \quad (7)$$

where EA_j is the theoretical potential of farming residues at j state from n type of crops, (GJ/year); $CA_{i,j}$ is the cultivated area of i crop at j state, hectares; $AP_{i,j}$ is agricultural production of i crop at j state, tonne per hectare; $PtR_{i,j}$ is the product to residue ratio of i crop at j state; $Av_{i,j}$ is the availability of residues for i crop according to current harvesting system at j state; HHV_i is the higher heating value of i crop, (GJ/tonne); i is the type of crop.

$$EW_j = \sum_{i=1}^n (ATH_{i,j} \times Rr_{i,j} \times HP_{i,j} \times HHV_i) \quad (8)$$

where EW is the theoretical potential of stemwood residues at state j from n type of stemwood, (GJ/year); $ATH_{i,j}$ is the annual timber harvest of i crop at j state, hectare; Rr is the residue ratio of i crop at j state, tonne/m³; $HP_{i,j}$ is the harvest percentage of i crop at j state, (%); HHV_i is the higher heating value of i crop, (GJ/tonne).

Biogas, the main product of manure digestion, is used for energy exploitations. Therefore, in order to provide the energy potential, the amount of manure can be multiplied with the specific biogas yield and the energy content of biogas. The theoretical potential of energy production from animal and poultry manure is derived from Eq. 9.

$$EM_j = \sum_{i=1}^n NH_{i,j} \times MpH_{i,j} \times BY_i \times BEC_i \quad (9)$$

where EM_j is the theoretical potential of manure at j state from n type of livestock, (GJ/year); $NH_{i,j}$ is the number of heads for the i type of livestock at j state, head; $MpH_{i,j}$ is the amount of manure for the i type of livestock at j state, tonne per head; BY_i is the biogas yields for the i type of livestock manure, in cubic meters (m³) per tonne; BEC_i is the energy content of gas produced from the i type of livestock manure (GJ/m³); and i is the type of livestock.

A straightforward approach to determine the theoretical and technical potential of biodegradable municipal solid waste (BMW) is based on thermal applications (like incineration). This method is described in Eq. 10.

Table 8 Acronym table

Acronym	Explanation
AHP	Analytic hierarchy process
AMSL	Above mean sea level
AP_{ij}	Agricultural production of i crop at j state
ATH_{ij}	Annual timber harvest of i crop at j state
BEC_i	Energy content of gas produced from the i type of livestock manure
BMW	Biodegradable municipal solid waste
BY_i	Biogas yields for the i type of livestock manure
CA_{ij}	Cultivated area of i crop at j state
EAj	Theoretical potential of farming residues at j state from n type of crops
EB_x	Biomass potential of biodegradable rural solid waste of village x
EMj	Theoretical potential of manure at j state from n type of livestock
ESx	Theoretical biomass potential of sewage Gas of village x
EW	Theoretical potential of stemwood residues at state j from n type of stemwood
FAHP	Fuzzy analytic hierarchy process
GEC	Energy content of gas produced
GIS	Geographic information system
GJ	Gigajoule
GY	Gas yield
HHV	Higher heating value
HP_{ij}	Harvest percentage of i crop at j state
IDW	Inverse distance weighting
MH_{ij}	Amount of manure for the i type of livestock at j state
NH_{ij}	The number of heads for the i type of livestock at j state
OC_x	Organic content of rural solid waste
OM	Organic dry matter of sewage sludge in rural sewage plants
PtR_{ij}	Product to residue ratio of i crop at j state
P_x	Population of village x
Rr	Residue ratio of i crop at j state
RWS_x	Percentage of the population served by rural waste services
RW_x	Rural waste production per capita of village x
S_x	Amount of sewage sludge treated in rural sewage of village x
TFN	Triangular fuzzy number

$$EB_x = RW_x \times P_x \times RWS_x \times OC_x \times HHV \quad (10)$$

where EB_x is the biomass potential of biodegradable rural solid waste of village x (GJ/year); RW_x is the rural waste production per capita of village x (tonnes/person/year); P_x is the population of village x (persons); RWS_x is the percentage of the population served by rural waste services (%); OC_x is the organic content of rural solid waste (dimensionless); HHV is the high heating value of biodegradable municipal solid waste (GJ/tonne); and x is the village.

Sewage sludge is produced during sewage treatment of wastewater. The obtained raw primary sludge needs to be further stabilized for the transportations. (Primary raw sludge is required to become more stable in order to be transported.) The treatment is done either anaerobically or aerobically. In the first case, the generated sewage gas is mainly composed of methane. Equation 11,

theoretically, shows the calculation of rural wastewater. This equation is a function of biogas thermal energy produced from rural sewage.

$$ES_x = S_x \times OM \times GY \times GEC. \quad (11)$$

ES_x is the theoretical biomass potential of sewage gas of village x (GJ/year); S_x is the amount of sewage sludge treated in rural sewage of village x (tonnes/year); OM is the organic dry matter of sewage sludge in rural sewage plants (percent); GY is the gas yield (m^3/kg organic dry matter); GEC is energy content of gas produced (GJ/ m^3).

When estimation of the HHV residual biomass magnitude was completed, the obtained information from evaluating the rural residual biomass using ArcGIS 10.3 was geo-referenced and prepared as the layers of various sources (five layers including the residual biomass resources'

Fig. 6 Total amount of rural waste (GJ/year)

Fig. 8 Zoning of gas pipeline (m)

Fig. 7 Amount of rural waste per person (GJ/year/people)

potential and population layer). Interpolation inverse distance weighting (IDW) was used based on the root mean square and calculated errors. The potential residual biomass production per capita and total HHV value per village were extracted in GIS for each village according to the rural population. Finally, a layer was created for the national gas transmission pipeline accessibility. The accessibility to natural gas and distance from the major energy carrier are reversely related. The residual biomass potentiometric map was created by considering the weight of accessibility to resource of the layers and the residual biomass information layers overlap in the GIS, and bioenergy development potential using the residual biomass resources was determined for each village, as shown in Fig. 5.

3 Determining the accessibility coefficient by FAHP analysis

The experts used the pair-wise comparison matrix to score the factors which were used for determination of the bio-waste resources accessibility coefficients. The comparison results matrix is given in Table 4.

The experts evaluated the parameters and rated each waste source regarding its accessibility importance. After

Fig. 9 Total amount of rural waste and zoning of gas pipeline (GJ/year/m)

being summed and homogenized, the results are listed in Table 5.

The factors' final and relative weights were determined for each one of the sources, which are given in Table 6.

Lastly, as shown in Table 7, each resource desirable accessibility was determined based on the relative value of each factor and its corresponding resource's score (Table 8).

4 Results

Based on the residual biomass resources and the obtained estimation for the 95 villages of the region, the collected information was processed by ArcGIS software and presented by geo-statistical method. The obtained maps include farm and horticulture waste, wastewater, livestock and poultry manure, household waste and agricultural residue. An estimation of the volume of the rural waste is shown in Fig. 6. As it can be seen, the highest production amount corresponds to the northern regions oriented toward the east and center. The density and area under cultivation of agricultural products are high in these regions, and usually, several crops are cultivated by the farmers, which increases the volume of produced waste.

An estimation of the volume of the rural waste per person that is calculated by summing the total rural waste layer (Fig. 6) and the population density layer (Fig. 2) is shown in Fig. 7. The amount of available wastes for energy production for any geographical location regarding the rural population distribution is presented in this map. As it can be seen, the highest values correspond to the north-west and southern regions, while the lowest values correspond to the northern and central regions.

In addition, to determine the rural residential areas' accessibility to the natural gas carriers, the gas pipeline transmission plan was prepared and zoned on the distance between the natural gas carrier and the areas. It was done in terms of the gas supply cost per person in the region. It is said by the experts that the lowest and highest costs of gas supply were for less than 250 m and more than 32,000 m from the major pipeline per person living in the area, respectively (Fig. 8). As it can be seen, in this region, the rural accessibility to the major energy carrier is reversely proportional to the factor of distance; as the area is farther, its accessibility is lower.

The new layer (Fig. 9) which shows the availability of energy per distance from the major pipeline is obtained by integrating the gas pipeline accessibility layer (Fig. 8) and the total rural waste layer (Fig. 6).

Fig. 10 Amount of rural waste per person and zoning of gas pipeline (GJ/year/people/m)

The new layer shown in Fig. 10 is obtained by merging the three layers of population dispersion (Fig. 2), the gas transmission line accessibility (Fig. 8) and the total rural residual biomass layer (Fig. 6).

5 Conclusion

The HHV of biomass resources and accessibility coefficients were used to quantify the residual biomass from agricultural and rural biowastes, and the potential extractable energy from the residual biomass resources, including wastewater, rural waste, livestock, horticulture wastes, farm wastes and poultry, was estimated. It was obtained that in 95 village of the region, a total amount of 1,191,022 GJ energy per year can be produced. The largest amount corresponds to the agricultural biowaste resources (987,986 GJ). The horticulture wastes and livestock waste have the potential of producing 94,416 GJ and 77,201 GJ energy, respectively. This amount was 18,712 GJ and 12,707 GJ for the rural sewage and rural waste, respectively. Compared to the whole region, the eastern villages have a better status for energy extraction from the biomass resources due to their access to the gas pipeline (40, 41, 58, 64, 65) and the estimated values of

waste (Fig. 7). The density population and dispersion layer were not considered in the present study. The condition of each area can be analyzed using Fig. 8, the rural biowaste accessibility of each person and the distance from the gas transmission line. As it can be seen, the southern regions consist of three villages in the positions #1, #2 and #3 and have a better chance of using the energy generating plans for providing the residential energy from the rural waste resources to the villages.

The total population of three villages in the region is 3772 people. Since these areas are located in high altitudes (2000 AMSL), they have low temperature, especially in winters. The severe winter weather forces a part of population to leave the area during the cold season. Mountain and forest roads are the only ways to access these villages which makes fuel transportation to these areas very difficult. Hence, using the waste resources to produce energy is so beneficial in the region and is an appropriate solution for the problem of these villages' accessibility to energy.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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