PREDICTION OF BIOMASS PELLET DENSITY USING ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM（ANFIS） METHOD
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基于自适应模糊神经网络算法（ANFIS）的生物质原料颗粒密度预测

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ABSTRACT
Coconut husk powder and corn stover powder were used as raw materials to produce formed particles, and four sets of uniaxial compression moulding devices were used to explore the effects of inner hole diameter of the forming moulds, depth of compression, and depth of conformal depth of the formed particles on the density of the particles. Sampling of the formed particles was carried out at the stage of stable compression force, the maximum pellet density of the coconut coir dust material is 1.53 g/cm³ (1530 kg/m³), and 1.23 g/cm³ (1230 kg/m³) of the corn stalk powder pellets are obtained. At the same time, in the process of the test, failure to compress the two biomass raw materials into pellets also occurred, indicating that the compression parameters studied in the experiment had a significant impact on the pellet quality. On the basis of the obtained pelleting test data, taking into account the nonlinear characteristics between pellet density and processing parameters involved, the adaptive neuro-fuzzy influence system (ANFIS) method was used to predict the pellet density of coconut coir dust and corn stover powder. The results show that the method is effective for predicting the density of biomass particles.

摘要
以椰子椰壳粉和玉米秸秆粉料为原料制取成形颗粒，利用四套单轴压缩成形装置，探索成形模具内孔直径、压缩深度、成形颗粒保形深度对颗粒密度的影响规律，在压缩力平稳阶段对成形颗粒进行取样，得到的椰子椰壳粉原料的最大颗粒密度为 1.53 g/cm³ (1530 kg/m³)*，玉米秸秆粉料颗粒的最大颗粒密度为* 1.23 g/cm³ (1230 kg/m³)*，同时在试验过程中两种生物质原料都出现了未成形的情况，表明了处理所研究压缩参数对颗粒质量影响显著。在已获得的颗粒成形试验数据基础上，考虑到颗粒密度与研究参数间的非线性特点，利用自适应模糊神经网络算法对玉米秸秆和椰子椰壳粉颗粒密度进行预测，结果显示该方法对预测生物质颗粒密度是有效的。*

INTRODUCTION
Accelerating clean energy transformation is critical to ensure timely decarbonization globally, in line with the goals of the Paris Agreement (*Aleluia et al., 2022*). There are many agricultural residues that can be considered as biomass raw materials, which can be densified into pellets or briquettes to replace traditional (fossil) fuels in developing countries (*Nath et al., 2023*). It is proved an effective way to increase biomass density, which has the added benefit of increasing the material's unit density as much as ten-fold (*Kumar et al., 2022; Stolarski et al., 2013*), resulting in a consistent shape and size of products (*Mani et al., 2004*), The biomass pellets were found to characteristically have higher calorific value, higher bulk and energy densities; and lower moisture content (*Kumar et al., 2022*).

Because of rising concerns about environmental pollution, global increases of energy cost and reduction in fossil fuel resources, many researchers have attempted to numerical modeling of biomass pelleting behavior and product quality parameters. In several works of literature, the nature and effects of different operating factors on biomass pelleting have been extensively studied, Saha in Bangladesh found that briquette made of coconut coir dust mixed with rice husk at ratio 1:1 appeared as the impressive economic feasibility (*Saha et al., 2016*). Regarding pellet physical properties, the effect of pelletizing moisture on pellet moisture content, bulk density, single pellet density and durability index were statistically significant (*Yılmaz et al., 2021*).

Die geometry also influences product properties like moisture content, bulk density, and durability (*Jr. & Sokhansanj, 1997*). The L/D (length to diameter) ratio of the pellet die can be a good metric for the degree of compression during pelleting (*Li et al., 2015*). An increase in the length of the pellet die increases the pelleting pressure, whereas an increase in the diameter of the pellet die decreases the pelleting pressure (*Holm et al., 2006*). The finite element modeling was employed to predict damage of biomass pellets (*Awny et al., 2022*), or discrete element method was adopted to simulate the compaction of bulky agricultural residues (*Horabik & Molenda, 2016; Xun et al., 2021*), also the development of constitutive models for the densification of biomass material to describe the mechanical behaviors in pellets production (*Huo L.et al., 2013; Kaliyan & Morey, 2009; Shang et al., 2011*)

Due to the wide divergence in physical and chemical properties of agricultural residues, pelleting conditions and pellet properties need to be determined for effective use. Adaptive neuro-fuzzy inference system (ANFIS), is a type of regression in which the experimental data is modelled by a nonlinear combination of parameters. The applications of ANFIS artificial intelligence in different disciplines have been reported, ANFIS significantly improving its capability to correlate uncertainties associated with computational modeling (*Ani & Agu, 2022*). The non-linear relationship between the dependent parameters like die diameter, compression depth, depth remain (defined as d_r, as illustrated in Fig.2) and feed, encourage usage of the soft-computing methods based on the concept of neural network. Therefore, the experiments used cylindrical pellets of corn stover and coconut coir dust to investigate density that affect handling and storage behavior of pellets. Data of pellet density under different pelleting parameters were collected, then these data were introduced into predicting biomass pellet density, this research attempted to create and implement a sophisticated algorithm to output reasonably density prediction in biomass pellet production.

MATERIALS AND METHODS

Materials

Corn stover and coconut coir were selected as biomass material for obtaining pellets, they were chopped and then ground using a mill (WILEY Laboratory Mill Model 4, ARTHUR H. THOMAS COMPANY). Particle distribution of two biomass material is presented in Table 1.

Table 1

Sieve analysis of corn stover and coconut coir dust

Sieve mesh space / mm	0.85	0.6	0.425	0.355	0.3	0.25	pan
Corn stover /%	100.00	70.55	48.40	24.09	18.07	12.76	7.86
Coconut coir / %	100.00	99.04	98.85	91.65	86.28	66.99	49.42

The moisture content of raw corn stover and coconut coir were both lower than 10% with wet basis for long-term storage under dry condition, it is below the commonly recommended range according to literature. To get the appropriate moisture content for obtaining pellets, raw materials after grinding were wetted by spraying purified water evenly, then the biomass material was put into water-tight bags, and it was being mixed manually for every 8 h to obtain a proper absorption of water and homogeneity. The moisture content in wet basis of corn stover and coconut coir dust is 20%±0.5% and 15%±0.2% respectively, and the initial bulky density under this condition for corn stover and coconut coir dust are 185±5.4 and 307±2.2 kg/m^3 respectively. Material that satisfied the required moisture content was stored in a container placed in ambient temperature of 10-15 ℃ for 48 h prior to pelleting. Raw materials and some pellets with different diameters produced in the test is shown in Fig.1.

Fig. 1 - Raw material of ground corn stover and coconut coir, and pellets

Experimental set-up

Pellets were obtained by using four sets of uniaxial compaction set-ups consisting of a cylinder and piston, the diagram of setup being shown in Fig. 2. The cylinder had an internal diameter *d* span of 6 to 25 mm, and a length span of 23 to 90 mm, in which the symbol d_c represents the depth in compression biomass material, and d_r represents the depth remain of cylinder for newly compacted pellet. During the pelleting process experiment, the support part is placed on the working table of a universal testing machine (MTS Systems Corporation, maximum force provided to 100 kN).

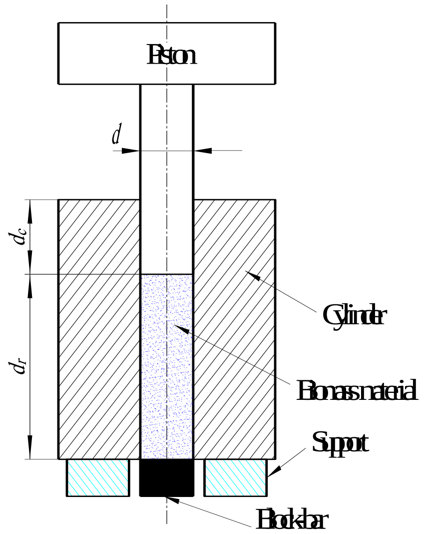

Fig. 2 - Diagram of uniaxial compaction set-up for pellet making

Experimental procedure

Corn stover and coconut coir are used as feedstock, compaction was carried out at different *d* and depth in compression d_c for different pellet obtaining set-up. Biomass material is fed into the cavity of the cylinder orifice, lower cavity end (outlet of hole) was blocked by a bar at first to establish the initial loading condition, also prevent the direct outflow of biomass material. After enough internal stress was set with 5-10 strokes of compression, the block bar is released as the continuous pellets production situation with roller-die biomass pelleting machine. As shown in Fig. 3, corn stover material is compacted into pellet, while the compression force is logged. Change of compression force depends on whether or not fix the part block-bar, it corresponds to three apparent phases of force, namely initial (the block-bar in Fig. 2 is set to close the orifice), transitional (the block-bar in Fig. 2 is removed and pellet start to move out the orifice) and steady phase. To eliminate the influence of initial loading conditions like preloading force etc., the pellet samples were collected in steady phase, the peak compression force in each stroke is close to 13000 N, after a gradual increasing trend of peak force in initial phase and transitional phase.

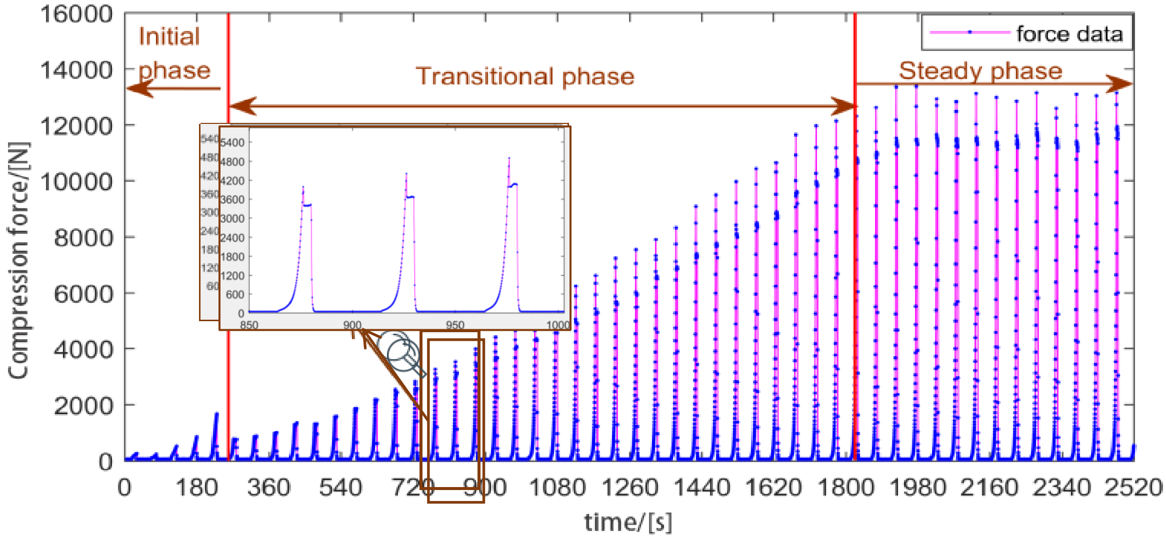

Fig. 3 - Diagram of uniaxial compaction setup for pellet making

The feeding amount *f* of biomass material of every stroke in each trial was the same in experiment, and the constant pushing/loading speed (14 mm/min) was also set in computer-controlled program to run the pelleting experiment.

Samples of biomass pellets produced in steady phase were sealed immediately in water-tight bags. After a week's preserving in a storage cabinet at approximate 18 ℃, then the diameter and height of pellet were measured with a caliper (0.02 mm resolution), and the average value of 5 measurements in different direction is adopted for each sample; the mass of each pellet sample was weighed with an electronic balance (0.01 g resolution, model ML4002E/03, Mettler-Toledo International Inc.). The unit density of pellets was calculated by dividing the mass by the volume of individual pellets.

Architecture of ANFIS model

Adaptive Neuro-Fuzzy Inference System (ANFIS), has been widely employed to represent or approximate a nonlinear system. It is a multilayer feed-forward network composed of nodes connected by directed links, in which each node performs a particular function on its incoming signals to generate a single node output. Figure 4 shows entire system architecture consists of five layers, namely fuzzy layer, product layer, normalized layer, de-fuzzy layer and output layer (*Jang, 1993*). With input/output data for given set of parameters, the ANFIS method models a fuzzy inference system (FIS) whose membership function parameters are tuned (adjusted) using either a backpropagation algorithm alone, or in permutation with a least squares type method. The parameter optimization is done in such a way during the training session that the error between the target and the actual output is minimized. A hybrid algorithm is used for optimization, which is the combination of least square estimate and gradient descent method. The parameters to be optimized in ANFIS are the premise parameters. These parameters define the shape of the membership functions (*Patel et al., 2014*). In order to reduce the error measure, any of several optimization routines can be applied after constituting MFs. The parameters set for an adaptive network allows fuzzy systems to learn from the data they are modeling (*Walia et al., 2015*).

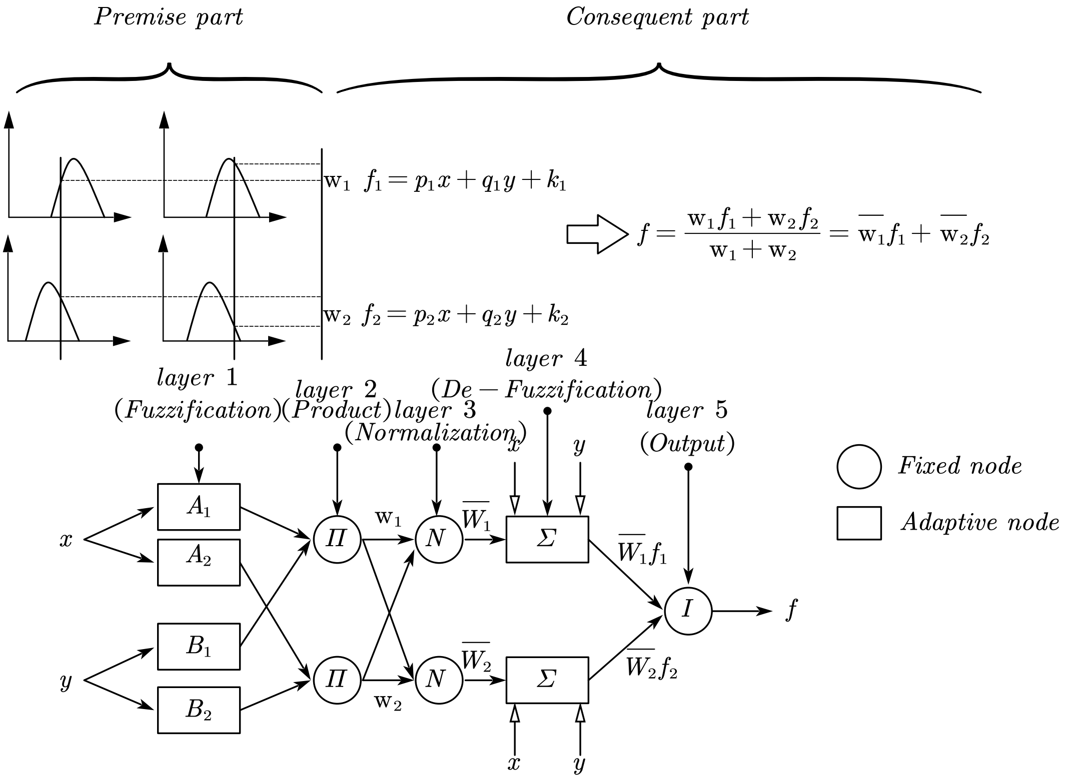

Fig. 4 - Basic architecture of an ANFIS model (Jang, 1993)

The architecture of the ANFIS in this study is shown in Fig. 5. In layer ‘input’, the die diameter *d*, compress depth d_c, remain depth d_r and feed *f*, are to be fuzzified. Inference process and rules are applied in layer ‘inputmf’ and layer rule. Calculation of output for each corresponding rules are carried out in layer ‘outputmf’ and then in layer density all outputs from layer ‘outputmf’ are combined to get one final ‘output’.

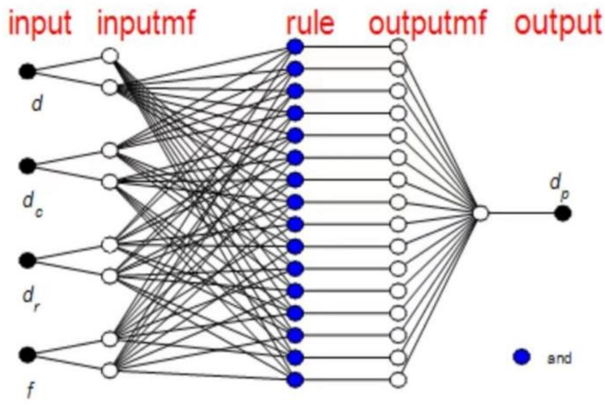

Fig. 5 - Architecture of ANFIS employed in this study

In this work, the membership function that defines how each point in the input space is mapped to a membership value, the generalized bell-shaped membership function is employed for all input variables, as defined in relation (1).

$$f(x;a,b,c)=\frac{1}{1+\left|(x-c)/a\right|^{2b}} \quad (1)$$

where: a, b, c are constant parameters to locate the center and shape of the curve (*Takagi & Sugeno, 1983*).

Fig. 6 shows the diagram of membership function of variables d, d_c, d_r and f in the ANFIS employed in prediction pellet density of both coconut coir dust and corn stover powder.

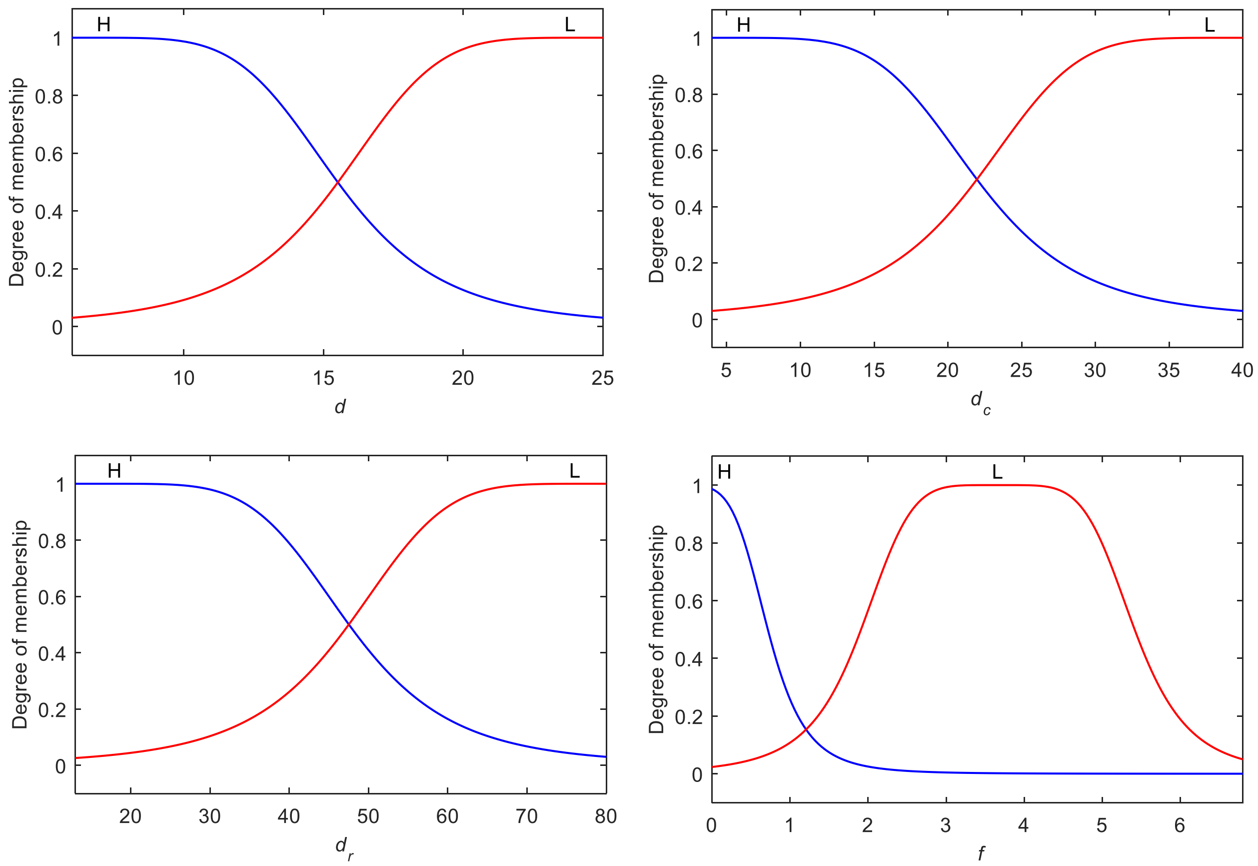

Fig. 6 - Membership function of four input variables in ANFIS model

The fuzzified information is processed using the rule base, composed of the fuzzy IF-THEN rules referred to as fuzzy control rules that must be well defined in order to control the given process (*Precup & Hellendoorn, 2011*). As shown in Table 2, the control rules in the ANFIS model used are given.

Table 2

Control Rules in ANFIS model

d	d_c	d_r	f	d_p
H	L	L	L	1
H	L	L	H	2
H	L	H	L	3
H	L	H	H	4
H	H	L	L	5
H	H	L	H	6
H	H	H	L	7
H	H	H	H	8
L	L	L	L	9
L	L	L	H	10
L	L	H	L	11
L	L	H	H	12
L	H	L	L	13
L	H	L	H	14
L	H	H	L	15
L	H	H	H	16

RESULTS

Pellet density under uniaxial compression

Density of pellets (expressed by the symbol d_p) made of coconut coir dust with uniaxial compression are given in Table 3, in order to get the influence of processing parameters on pellet density; 50 tests were conducted in making pellets of coconut coir dust. Parameters involved in each run are d, d_c, d_r and f, which represents the diameter, depth in compression, depth remain as defined previously in Fig. 2, and feed amount in gram respectively. The maximum pellet density was obtained in run No. 43, namely 1.53 g/cm^3 (1530 kg/m^3), which was produced in cylinder of internal diameter 6 mm with feed 0.11 g per stroke. Under the same conditions, other 2 replications also produced relatively high-density pellets, as indicated in run No. 44 and 45. The minimum density 0.31 g/cm^3 (310 kg/m^3) was obtained in run No. 2, the diameter being 25 mm with feed of 6.79 g per stroke. In the process of compressing biomass material, even though the pellets in initial phase are close to 1.20 g/cm^3, the compression force decreased gradually in transitional phase, and finally got close to 0 N in steady phase, the feeding material run through the cylinder hole in bulky format.

Table 3

Density data of coconut coir dust pellet in uniaxial compression

Run No.	d [mm]	d_c [mm]	d_r [mm]	f [g]	d_p [g/cm^{-3}]	Run No.	d [mm]	d_c [mm]	d_r [mm]	f [g]	d_p [g/cm^{-3}]
1	25	36	54	6.79	0.38	26	20	10	66	1.21	0.57
2	25	36	54	6.79	0.31	27	20	10	66	1.21	0.68
3	20	20	56	2.41	0.79	28	6	8	15	0.09	1.41
4	20	20	56	2.41	0.61	29	6	8	15	0.09	1.06
5	20	40	36	4.83	0.43	30	20	30	46	3.62	0.95
6	20	40	36	4.83	0.43	31	20	30	46	3.62	0.95
7	20	40	36	4.83	0.50	32	20	30	46	3.62	0.90
8	25	16	74	3.02	0.92	33	20	8	68	0.97	0.80
9	25	16	74	3.02	0.95	34	20	8	68	0.97	0.75
10	25	26	64	4.90	0.51	35	20	8	68	0.97	0.67
11	25	26	64	4.90	0.52	36	12	5	46	0.22	1.10
12	25	24	66	4.52	0.54	37	6	8	15	0.09	0.62
13	25	10	80	1.89	0.49	38	12	25	26	1.09	1.10
14	25	10	80	1.89	0.46	39	12	25	26	1.09	0.61

Run No.	*d* [mm]	d_c [mm]	d_r [mm]	*f* [g]	d_p [g/cm^{-3}]	Run No.	*d* [mm]	d_c [mm]	d_r [mm]	*f* [g]	d_p [g/cm^{-3}]
15	25	10	80	1.89	0.40	40	12	25	26	1.09	0.97
16	6	4	19	0.04	1.36	41	12	15	36	0.65	1.06
17	6	4	19	0.04	1.24	42	12	15	36	0.65	0.98
18	12	20	31	0.87	1.19	43	6	10	13	0.11	1.53
19	12	20	31	0.87	1.39	44	6	10	13	0.11	1.17
20	6	4	19	0.04	1.52	45	6	10	13	0.11	1.50
21	6	4	19	0.04	1.30	46	12	10	41	0.43	1.26
22	6	4	19	0.04	1.47	47	12	10	41	0.43	1.10
23	12	25	26	1.09	1.25	48	6	8	15	0.09	1.24
24	12	25	26	1.09	1.25	49	6	8	15	0.09	1.24
25	20	10	66	1.21	0.65	50	6	6	17	0.07	1.13

Similar behaviors also could be seen in pellet making of corn stover pellet, 52 runs were conducted in the experiment as shown in Table 4. The maximum pellet density obtained in run No.8, namely 1.23 g/cm^3 (1230 kg/m^3), which was produced in cylinder of internal diameter 12 mm with feed 0.29 g per stroke. Under the same conditions, other 2 replications also produced relatively high-density pellet, as indicated in run No. 9 and 10. The minimum density 0.17 g/cm^3 (170 kg/m^3) was obtained in run No. 29 and 43-49.

Table 4

Density data of corn stover pellet in uniaxial compression

Run No.	*d* [mm]	d_c [mm]	d_r [mm]	*f* [g]	d_p [g/cm^{-3}]	Run No.	*d* [mm]	d_c [mm]	d_r [mm]	*f* [g]	d_p [g/cm^{-3}]
1	12	25	26	0.48	0.68	27	25	26	64	2.17	0.58
2	12	25	26	0.48	0.69	28	25	16	74	1.34	0.49
3	12	25	26	0.48	0.71	29	6	4	19	0.02	0.17
4	12	25	26	0.48	0.68	30	25	10	80	0.83	0.58
5	12	5	46	0.10	1.04	31	25	10	80	0.83	0.68
6	12	5	46	0.10	0.94	32	25	10	80	0.83	0.67
7	12	5	46	0.10	0.76	33	20	20	56	1.07	0.76
8	12	15	36	0.29	1.23	34	20	20	56	1.07	0.76
9	12	15	36	0.29	1.02	35	20	20	56	1.07	0.66
10	12	15	36	0.29	1.17	36	20	20	56	1.07	0.74
11	12	10	41	0.19	1.04	37	25	16	74	1.34	0.57
12	12	10	41	0.19	1.10	38	25	16	74	1.34	0.58
13	12	10	41	0.19	1.05	39	25	16	74	1.34	0.57
14	20	10	66	0.53	1.07	40	6	6	17	0.03	0.89
15	20	10	66	0.53	0.83	41	6	6	17	0.03	0.75
16	20	10	66	0.53	0.91	42	25	16	74	1.34	0.49
17	20	30	46	1.60	0.68	43	20	40	36	2.14	0.17
18	20	30	46	1.60	0.64	44	20	40	36	2.14	0.17
19	20	30	46	1.60	0.65	45	20	8	68	0.43	0.17
20	20	20	56	1.07	0.79	46	20	8	68	0.43	0.17
21	20	20	56	1.07	0.76	47	25	36	54	3.00	0.17
22	25	16	74	1.34	0.66	48	25	36	54	3.00	0.17
23	25	16	74	1.34	0.71	49	25	36	54	3.00	0.17
24	25	16	74	1.34	0.66	50	12	20	31	0.38	0.99
25	25	26	64	2.17	0.54	51	12	20	31	0.38	0.98
26	25	26	64	2.17	0.56	52	12	20	31	0.38	0.90

Prediction of pellet density with ANFIS

Sugeno type of ANFIS (*Michio, 1985*) model was implemented in this work, 35 data were selected from both Table 3 and Table 4 respectively, for training the ANFIS model, and the rest of the data was used in validating the model.

Fig. 7 and Fig. 8 depicts the comparisons of data acquired from compaction experiment and prediction, it can be seen that the ANFIS model provided the most dominant accuracy for describing pellet density with a simpler structure, the average error in training ANFIS model is 0.123 for material coconut coir dust pellet, and the value is 0.056 for corn stover powder, this also indicated that the corresponding data is in good agreement as shown in Fig. 7 and Fig. 8. The average error in checking the ANFIS model is 0.169 for coconut coir dust pellet, and 0.149 for corn stover powder. This also shows that the ANFIS model effectively learned from the experimental data.

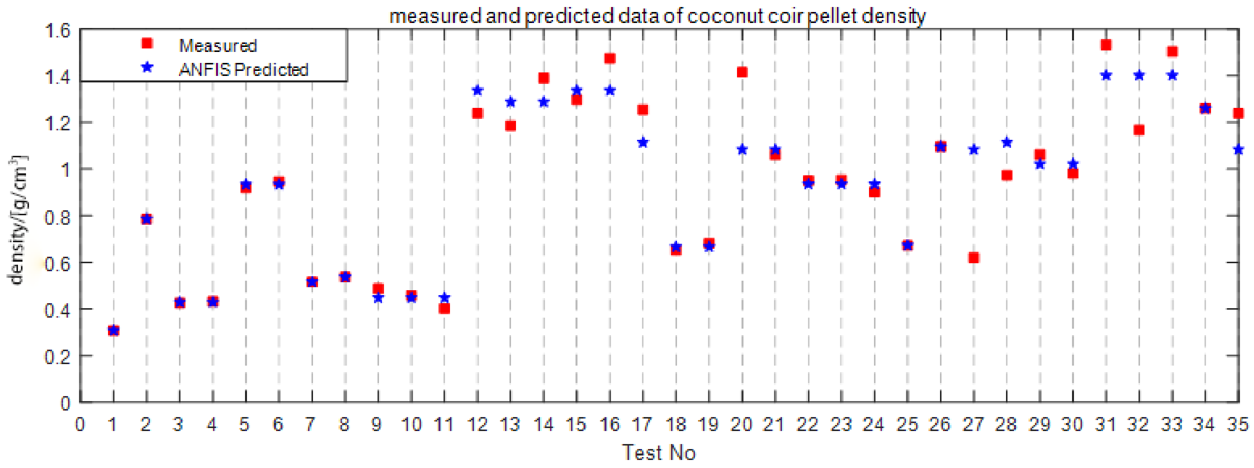

Fig. 7- Comparison of measured and ANFIS predicted values of coco coir pellet density

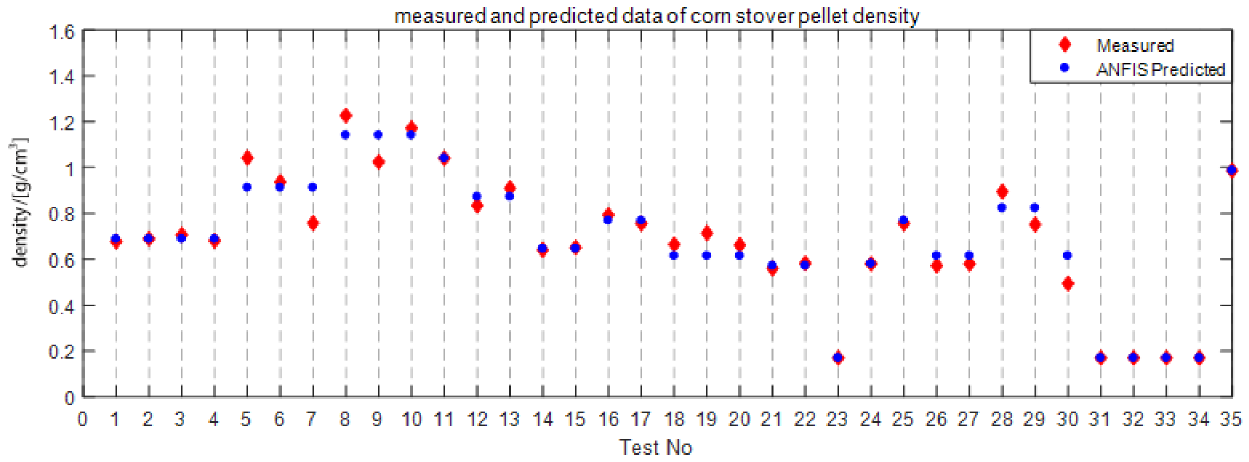

Fig. 8- Comparison of measured and ANFIS predicted values of corn stover pellet density

CONCLUSIONS

This study investigated the feasibility of coconut coir dust and corn stover powder as a suitable biomass material for pellet production, and the experimental data was conducted considering the key factors like cylinder diameter, depth in compression, depth remain and feed, in pellet making process, pellet samples were collected in steady phase, which was more consistent with the actual production situation, the failure in compaction and blocking behaviors were also observed in uniaxial compression. The ANFIS model was introduced to predict the pellet density. It is indicated that ANFIS model gave relatively lower errors for the predicted biomass pellet density and provided good agreements with experimental data, the ANFIS provide a feasible way to describe the nonlinear relationship between quality parameters and processing variables in biomass pellet producing.

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