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Design of a Circular Economy Model for Corn by-Products

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ABSTRACT

The waste generated from corn cultivation remains underutilized, necessitating studies on its potential for economic value. The objective of this research was to study the cicular economi model to maximally utilize corn wastes. Corn plant samples were collected from 20 different locations. The corn plants were separated into husks, cobs, grains, leaves, and stems, then weighed to obtain physical data in the form of the percentage weight of each part. The parts of the corn plants were chemically analyzed to determine their cellulose, hemicellulose, lignin, extractable substances, ash content, and C/N ratio. In addition, interviews were conducted to assess the potential for developing derivative products and market prospects. Exponential Comparison Method (ECM) was used to determine which derivative products to be developed within the circular economy model design. The study revealed the dry weight composition of corn plant as follows: husks 6.34%, cobs 7.19%, grains 31.65%, leaves 17.24%, and stems 37.58%. The chemical composition of corn plant was hemicellulose 27.55%, cellulose 29.26%, lignin 11.51%, extractive substances 30.19%, and ash content 1.49%. The C/N ratio values of the corn plant by-products were: husks 49.79, cobs 95.11, leaves 30.99, and stems 56.21. Based on the ECM calculations, silage was selected as the top priority to be developed, with a score of 121,972,607.

1. INTRODUCTION

The increase in corn (*Zea mays*) production affects the rise in the amount of waste generated. This waste consists of stems, leaves, husks, and cobs. This increase is also influenced by the expansion of cultivation land, which has been converted from other land uses. The expansion of cultivation land also impacts the increase in the number of corn plants that are not utilized (by-products). Unlike shelled corn products, the residual corn plants as by-products of cultivation are still not optimally utilized. These by-products include stems, leaves, husks, and cobs. They are neglected due to the lack of knowledge and processing technology owned by farmers and the absence of businesses that use corn plant by-products as raw materials. Unused and accumulated corn plant residues can become a source for the development of plant pests (Pratama *et al*., 2015).

The easiest way for farmers to eliminate them is through burning. This handling method is considered more effective and efficient for farmers. However, burning activities carried out by farmers disrupt the community's environment due to the decline in air quality (Kasim *et al*., 2021). This can affect health, such as causing respiratory infections and reducing visibility.

The concept of the circular economy emerges as a wise approach to human activities concerning the environment and future generations. A circular economy promotes the efficient use of natural resources, reduces waste, and extends the product lifecycle through activities such as recycling, recovery, and reuse. By employing circular practices, a circular economy can create new job opportunities in sectors such as recycling, repair, reuse, and waste utilization as raw materials. Through sustainable business innovation and development, a circular economy can help create productive jobs and generate inclusive economic growth that is environmentally friendly (Multazam, 2023). According to Anwar (2022), to move towards a green economy, eight main economic sectors need to be considered to: reduce poverty, invest in natural capital and its restoration, create jobs and enhance social equity, and promote renewable energy and energy efficiency.

According to Tongwane *et al*. (2016), the high emissions generated in corn cultivation are due to land management, the use of synthetic chemical fertilizers, and plant waste in the cultivation area. According to Kumar *et al*. (2021), the increase in emissions in corn cultivation is also influenced by the application of N fertilizers. Utilizing corn waste contributes to environmental sustainability by converting energy and nutrients from materials that cannot be used by humans (Achardi *et al*., 2021).

The feasibility of agricultural growth is based on the efficiency of land use, labor, and other infrastructure in relation to technological advancements, social innovations, and new business models (FAO, 2017). Based on the concept of Circular Economy, increasing resource efficiency and reducing waste production are unexplored economic opportunities that have the potential for economic growth (Ghisellini *et al*., 2016). Circular Economy is recommended as an approach to economic activities that aligns with sustainable environmental and economic development (Ellen MacArthur Foundation, 2015). Based on the above prepositions, the objective of current research is to evaluate some derivative products from corn wastes based on the Circular Economy concept.

2. MATERIALS AND METHODS

2.1. Materials

In this study, the sample materials of corn plants were obtained from the farmers' cultivation land in Baradatu and Gunung Labuhan Districts, Way Kanan Regency. The questionnaires were filled out by corn farmers. Figure 1 showed the map of Baradatu and Gunung Labuhan District in Way Kanan Regency, as the sampling locations for corn plants.

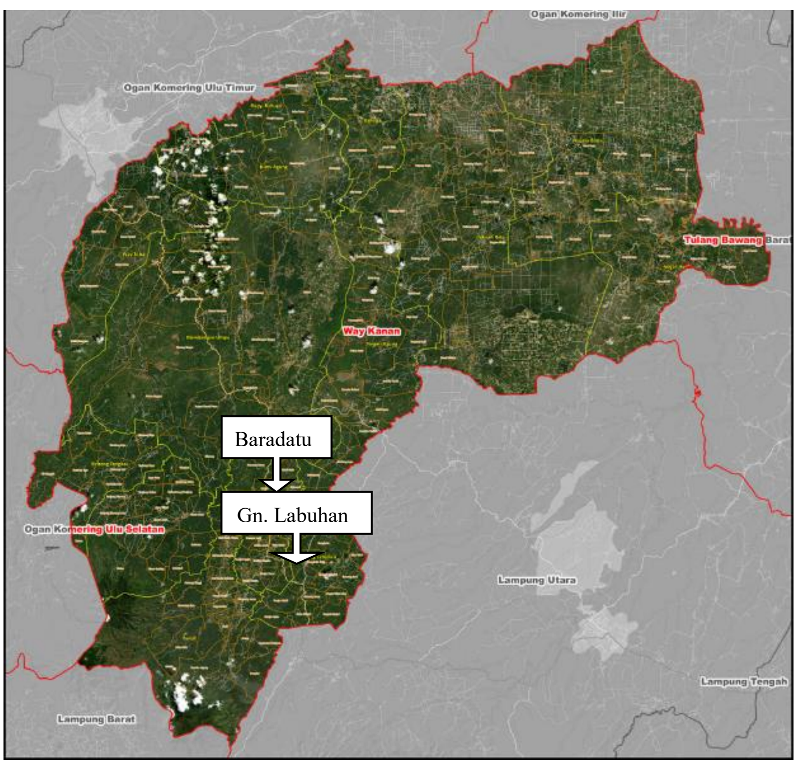

Figure 1. Research location (Baradatu and Gunung Labuhan Distric) in Way Kanan Regency

2.2. Questionnaire

The research activities were carried out in the field using interview and survey methods. The form of the interview conducted was unstructured with open-ended questions, giving participants the freedom to provide their views freely and allowing researchers to ask in-depth questions. Questionnaires and interviews are used to determine which parts of the corn plant are still the main source of income, the utilization of corn by-products by farmers and their handling, farmers' knowledge of processing by-products and their derivative products, the opportunities for using derivative products from processing corn by-products by farmers, farmers' ability and interest in the business potential of post-use derivative products, and competitors with similar products. The participants involved are farmers who are part of farmer groups in corn cultivation centers, where at the time of the research, these farmers were cultivating corn. In each district, 10 farmers were selected, whose corn plants had reached harvest age at the time of the study.

2.3. Physical and Chemical Analysis

Physical analysis of the corn waste samples was done by separating the parts based on grain, stems, leaves, husk, and cob. These parts were then weighed to determine the percentage weight of each part. Chemical analysis of corn plant by-product samples used the bomb calorimeter method to determine calorie values. The chemical extraction method is used to determine the content of hemicellulose, cellulose, lignin, and extractives. The gravimetric method is used to determine the ash content. An elemental analyzer was used to determine the C/N ratio value.

2.4. Determination of Derivative Products

The determination of derivative products was done using the Exponential Comparison Method (ECM) for product criteria and alternatives. ECM is one method for determining the priority order of decision alternatives with multiple criteria. This technique assists decision-makers in using well-defined model designs at each process stage (Marimin, 2004). The total score was calculated as the following:

$$\text{Total Score } (TS_i) = \sum_{j=1}^{m} (RK_{ij})^{TKK_j} \tag{1}$$

where TS_i is total score of the i^{th} alternative, RK_{ij} is degree of relative importance of the j^{th} criterion in the i^{th} decision choice (value of weighting criteria), TKK_j is degree of importance of the j^{th} decision criterion (value of alternatives weight based on criteria, $TKK_j > 0$; integer), n is number of decision choices, and m is number of decision criteria

Criteria considered in the research include availability of raw materials, market opportunities, market absorption capacity, business sustainability, market prices, competitors, and potential derivative products post-use. Alternatives considered include liquid smoke, biochar, compost, mushroom cultivation media (MCM), and feed. These products become alternative because of extensive research, relatively easy manufacturing processes, and low costs investment.

2.2.5. Development of Circular Economy model design

The development of the Circular Economy model design is based on the capabilities and interests of farmers in running new business opportunities from the derived products they produce. This Circular Economy model design is intended to maximize the utilization of corn plant by-products in a closed-loop business cycle. The economic parameters used in the circular economy for corn by-products include resource utilization, value creation, and technological innovation. This design emphasizes green economy 0% waste, where the end product of corn plant by-products is returned to nature in the form of organic fertilizer.

3. RESULTS AND DISCUSSION

3.1. Physical Analysis

Whole corn plant samples (husk, cob, grain, leaves, and stems) were taken from 20 different locations in each field. One stalk sample was taken from each location, so the total number of corn plant samples was 20 stems. The parts of the corn plant are presented in the following Figure 2. The results of the physical analysis of the sample parts' weight are presented in Table 1. The weight percentage of corn plant parts is as follows: husk 6.34%, cob 7.19%, grain

31.65%, leaves 17.24%, and stem 37.58%. Thus, it is known that 31.65% consists of corn grain as the main product, while the remaining 68.35% is by-products. To determine the weight percentage of corn plant by-products, weight conversion calculations were carried out. The weight percentage of corn plant by-products is presented in Table 2. The by-product of corn plant is as follows: husk 9.3%, cob 10.5%, leaves 25.2%, and stem 55.0%.

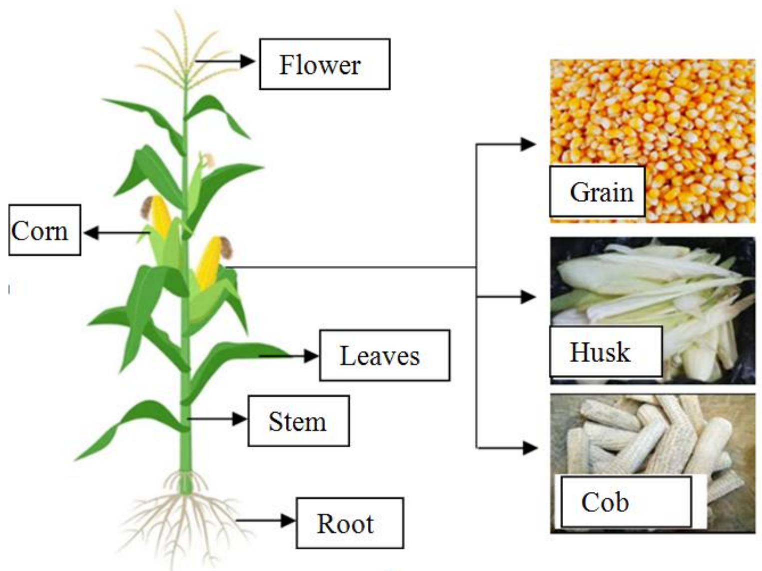

Figure 2. Parts of the corn plant (Shutterstock.com)

Table 1. Results of physical analysis of corn samples from two districts in dry basic

Districts	Total Biomass (g)	Weight of Corn Plant Parts (g)				
		Husk	Cob	Grain	Leaves	Stem
Baradatu	8038	487 (6.06)	538 (6.69)	2367 (29.45)	1604 (19.96)	3042 (37.85)
Gunung Labuhan	5675	376 (6.63)	436 (7.68)	1921 (33.85)	824 (14.52)	2118 (37.32)
Average	6856.5	431.5 (6.34)	487 (7.19)	2144 (31.65)	1214 (17.24)	2580 (37.58)

Note: Numbers in parenthesis percentage of total biomass

Table 2. Percentage of by-product weight

No	Part of Plant	Percentage of corn weight (%)	
		All parts	By-product
1	Stem	37.6	55.0
2	Leaves	17.2	25.2
3	Husk	6.3	9.3
4	Cob	7.2	10.5
5	Grain	31.65	
	Total	100.00	100.00

3.2. Chemical Analysis

The results of the chemical analysis of the corn plant sample parts based on caloric value, extractive substances, hemicellulose, cellulose, lignin, and ash content are presented in Table 3. Based on Table 1 and Table 3, the contents of hemicellulose, cellulose, lignin, extractives, and ash in the corn plant by-products can be calculated. The calculation results are presented in Table 4. The chemical content in corn plant by-products calculated from the material weight is as follows: hemicellulose 27.55%, cellulose 29.26%, lignin 11.51%, extractives 30.19%, ash content 1.49%.

Table 3. Chemical analysis results of corn plant by-product samples (caloric value, extractive, hemicellulose, cellulose, lignin, ash)

No	Sample/ Code	Calorific Value		Composition				
		cal/g	MJ/kg	E (wt%)	Hc (wt%)	C (wt%)	L (wt%)	Ash (wt%)
1	Stem	4,329.45	18.11	35.14	22.72	30.03	10.40	1.71
	Stem *	4,497.34	18.82	35.97	22.85	29.94	10.55	0.69
2	Cob	4,307.12	18.02	10.58	41.64	29.26	17.84	0.68
	Cob *	4,478.29	18.74	9.62	42.62	28.72	18.54	0.51
3	Husk	4,575.50	19.14	23.11	39.48	27.37	9.80	0.24
	Husk *	-	-	22.45	38.74	27.11	10.58	1.13
4	Leaves	4,556.52	19.06	29.61	28.01	28.03	11.43	2.91
	Leaves *	-	-	29.56	27.22	29.04	11.49	2.69

Note: * = Test repetition; E = Extractives; Hc = Hemicellulose; C = Cellulose; L = Lignin; Ash = Ash content

Table 4. Hemicellulose, cellulose, lignin, extractives, and ash contents in corn plant by-products

No	Corn Plant Part	Chemical Composition of Corn Plant By-products (%)					
		Hc	C	L	E	Ash	Total
1	Stem	12.53	16.49	5.76	19.55	0.66	54.98
2	Leaves	6.97	7.20	2.89	7.46	0.71	25.22
3	Husk	3.63	2.53	0.95	2.11	0.06	9.28
4	Cob	4.43	3.05	1.91	1.06	0.06	10.52
	Total	**27.55**	**29.26**	**11.51**	**30.19**	**1.49**	**100.00**

Note: Hc = Hemicellulose; C = Cellulose; L = Lignin; E = Extractives; Ash = Ash content

Table 5. Results of chemical analysis of C/N ratio of corn plant by-products

Corn Plant Part	N Area	C Area	H Area	N %	C %	H %	C/N Ratio	C/H Ratio
Stem	2.401	94.035	51.762	1.07	60.28	9.18	56.34	6.57
Leaves	4.054	86.807	48.463	1.74	54.01	8.35	31.04	6.47
Husk	2.703	93.600	53.067	1.18	58.84	9.05	49.86	6.50
Cob	1.497	100.049	53.929	0.66	62.31	9.28	94.41	6.72

Table 6. C/N Ratio of corn plant by-products

No	Corn Plant Part	Weight of corn by-product samples (%)	C/N Ratio of corn plant samples	C/N Ratio of corn by-products
1	Stem	54.98	56.34	30.97
2	Leaves	25.22	31.04	7.83
3	Husk	9.28	49.86	4.63
4	Cob	10.52	94.41	9.93
	Total	100		**53.36**

In addition to the aforementioned chemical content tests, a C/N Ratio test was also conducted on each part of the corn plant by-products. The C/N Ratio test is used to determine the ratio of carbon (C) to nitrogen (N). Information related to the C/N Ratio is needed if the product involves the use of microbes in its processing. The results of the C/N Ratio test on the samples of corn plant by-products are presented in Table 5. The C/N ratio values of corn plant by-product samples are as follows: stem 56.34, leaves 31.04, husk 49.86, and cob 94.41. Based on Tables 1 and 5, the C/N ratio content of corn plant by-products can be calculated. The calculation results are presented in Table 6. Based on Table 6 above, the overall C/N ratio of corn plant by-products (stem, leaves, husk, and cob) is 53.36.

3.3. Determination of Derivative Products

The product alternatives proposed in this study are silage made from leaves and stem, mushroom cultivation media made from stem and cobs, compost made from all corn plant waste, biochar made from cobs, and liquid smoke made from all plant waste. Based on the results of interviews with corn cultivation farmer groups, physical analysis, and chemical analysis of corn plant by-products, an analysis of product determination was carried out using the Exponential Comparison Method (ECM). The alternative derivative products are:

3.3.1. Silage

Silage is animal feed derived from plants/plant residues. Raw materials for silage include agricultural waste such as rice straw, corn straw, sugarcane tops, and others (Syahniar & Subagja, 2018). According to Pratama (2019), the maximum level of indigestible crude fiber is 18% of the total feed weight for livestock. The research results (Islamiyati *et al*., 2017) that crude fiber content decreases and protein increases with the length of incubation time; therefore, silage is a viable alternative.

3.3.2. Mushroom Cultivation Media

Corn cobs have the potential to be an alternative growing medium in mushroom cultivation due to their high cellulose content, which is 41% cellulose, 36% hemicellulose, 6% lignin, and silica. Additionally, corn cobs are easily obtainable, sufficiently available, and nutritionally adequate (Sari *et.al*., 2022). According to Cahyana *et al*. (1997), good wood shavings used as a mushroom cultivation medium come from wood that does not contain much sap. Wahyuningsih *et al*. (2022) stated that when straw undergoes fermentation and decomposition, large amounts of carbohydrates and organic compounds become available, which mushrooms utilize as a nutrient source in their growing medium. Research by Anggraeni (2007) shows that the addition of cob flour increases mushroom yields. Based on these findings, the use of corn plant by-products as a cultivation medium for mushrooms is considered a viable alternative.

3.3.3 Compost

Corn plant residues are organic materials, thus they can be processed into solid organic fertilizer in the form of compost. Compost plays a significant role in the plant production cycle as it benefits soil and plants by improving soil structure and pH, and enhancing soil microbe life and micro-elements through decomposition/composting (Dahliana *et al*., 2022). Composting corn plants is considered to have more environmental benefits and sustainability. Through composting, the production of smoke and greenhouse gases from burning corn waste can be reduced significantly. Corn compost contains the macro and micronutrients required by plants, although not at levels as high as synthetic fertilizers or animal manure. Utilizing compost made from corn waste can reduce farmers' reliance on synthetic fertilizers and, more importantly, lower pollution levels. Therefore, using all corn waste as compost is deemed a viable alternative.

3.3.4. Biochar

Biochar is biomass waste that is not utilized, such as rice husks, palm shells, coconut shells, cobs, and other agricultural waste through an incomplete combustion process (Putri *et al*., 2017; Mautuka *et al*., 2022). Cobs have the highest lignin content among parts of the corn plant, making them the most difficult part to decompose naturally. This characteristic is advantageous for processing cobs into biochar. Tripathi *et al*. (2016) reveal that hemicellulose, cellulose, and lignin are the main components of biomass that affect pyrolysis products. (Kloss *et al*., 2012) state that the content of lignin, hemicellulose, and cellulose influences biochar formation. According to Sukmawati (2020), biochar made from cobs has the highest carbon content compared to palm kernel shells. In addition to being a fuel source, biochar can be applied as a soil amendment in agricultural fields. Given this, utilizing corn cobs as biochar can be considered an alternative product to offer.

3.3.5. Liquid Smoke

Liquid smoke is obtained by pyrolysis of corn plant waste, the smoke produced is condensed with flowing cold water and collected. Although not widely known among the public, liquid smoke from corn plant waste can be used as a food additive aimed at preservation and flavor/aroma formation of food ingredients (Mehang *et al*., 2022). Liquid smoke has long been used as a food preservative due to its antimicrobial properties, ability to provide aroma, and its pH-lowering effect (Swastawati *et al*., 2007; Handayani *et al*., 2018). Liquid smoke can impart color, flavor, and aroma to food (Ginayati *et al*., 2015). The use of liquid smoke in food requires distillation because it still contains high levels of tar. Corn waste as a raw material for liquid smoke presents a good opportunity, as it has not yet been utilized and is available in large quantities. Consideration of product alternatives is presented in Table 7.

Table 7. Considerations for alternative products derived from corn plant by-products and their potential

Product Type	Part of corn plant	Utilization	Market opportunities/ participant interest	By-products after use	Opportunities for by-product utilization after use
Silage	Leaves, Stems, Husks, Cobs	Packaged feed for livestock that can be enriched and has long shelf life	There are opportunities and interest from participants or farmers, many small farmers and some livestock collectors	Manure of good quality, because it is not contaminated by weed grains	Solid organic fertilizer, worm cultivation medium
Hay	Leaves, Stems, Husks	Dry livestock feed that cannot be enriched	Less interested by farmers/participants due to less practical handling and not liked by livestock	Manure	Solid organic fertilizer, worm cultivation medium
Corn Straw	Leaves, Stems, Husks	Dry livestock feed that cannot be enriched	Less interested by participants or farmers due to less practical handling and not liked by livestock	Manure	Solid organic fertilizer, worm cultivation medium
Mushroom Cultivation Media	Stems, Cobs	Mushroom culti-vation medium in bag logs	There are opportunities but still less interested by participants, only a few mushroom cultivators.	Log bag residue	Solid organic fertilizer, worm cultivation medium
Compost	Leaves, Stems, Husks, Cobs	Organic fertilizer	There are opportunities but still less interested by farmers, fertilizer quality is considered lower than manure	--	--
Biochar	Cobs	Bricket	There are opportunities but still less interested by participants, LPG gas is considered more practical	Ash	Organic fertilizer mix
Liquid Smoke	Leaves, Stems, Husks, Cobs	Organic pesticide	There are opportunities but still less interested by participants, chemical pesticides are considered more effective and efficient	--	--

3.3.6. Weighting of Criteria and Alternatives

Once the importance degree/weight predicate and weight value are determined, the alternative criteria are assigned values based on expert opinions, based on the results of questionnaire recaps and interviews with respondents in Table 8. The input columns for weighting are presented in Table 9.

After weighting, calculations are made to obtain the highest score. Based on formula, the weights of the criteria are raised to the power of the weights of the alternatives. The exponentiation is presented in Table 10. After calculations in Table 10, the total ECM values for alternative products are as follows: Liquid smoke 50,664,297, Biochar 13,382,377, Compost 64,984,254, Mushroom cultivation medium 27,684,408, and Livestock feed (silage) 121,972,607. Therefore, the selected priority product is Livestock feed (silage) with an ECM value of 121,972,607.

Table 8. Importance levels and weight values for product criteria and alternatives

Weight Predicate	Very Important	Important	Fairly Important	Less Important	Not Important
Weight Value	9	7-8	5-6	3-4	1-2

Table 9. Weighting of criteria and alternatives for products made from corn plant by-products

No	Criteria	Weighting	Product Alternative Weight				
			Liquid Smoke	Biochar	Compost	MCM	Silage
1	Availability of raw materials	8	9	7	9	8	9
2	Market opportunities	8	5	5	8	7	8
3	Market absorption	9	4	4	5	4	7
4	Business sustainability	7	8	8	8	8	8
5	Market price	7	5	5	7	6	8
6	Competitors	7	9	9	6	7	7
7	Potential for derivative products after use	8	3	3	3	6	8

Table 10. Exponentiation of criteria weights to alternative weights

Criteria	Exponentiation	Total Score	Priority
Liquid Smoke	$= 9^8 + 5^8 + 4^9 + 8^7 + 5^7 + 9^7 + 3^8$	50.664.297	3
Biochar	$= 7^8 + 5^8 + 4^9 + 8^7 + 5^7 + 9^7 + 3^8$	13.382.377	5
Compost	$= 9^8 + 8^8 + 5^9 + 8^7 + 7^7 + 6^7 + 3^8$	64.984.254	2
MCM (Mushroom Cultivation Media)	$= 8^8 + 7^8 + 4^9 + 8^7 + 6^7 + 7^7 + 6^8$	27.684.408	4
Silage	$= 9^8 + 8^8 + 7^9 + 8^7 + 8^7 + 7^7 + 8^8$	121.972.607	1

According to Pratama (2019), the maximum indigestible crude fiber content is 18% of the total weight of livestock feed. Based on chemical test results in Table 4, the corn plant by-products contain 27.55% hemicellulose, 29.26% cellulose, 11.51% lignin, and 1.49% ash. The hemicellulose and cellulose contents can be enzymatically broken down by lactic acid bacteria during the fermentation process and the digestive system of ruminants, and fermentation can also reduce lignin content. Referring to the ideal C/N ratio for making silage feed, Darmin *et al*. (2022) stated that the best C/N ratio for making silage is 30. Based on chemical analysis of corn plant by-products, the C/N ratio obtained is 53.3431, which is 23.3431 higher than the ideal requirement. The C/N ratio can be reduced by adding other materials with high protein (nitrogen) content; the N value can also be increased by adding urea to the corn plant by-products before fermentation. Based on the above explanation, it can be concluded that corn plant by-products are considered suitable to be made into good livestock feed.

3.4. Development of Linear Economy into Circular Economy Model

The linear economy consists of three important elements: material, energy, and information/knowledge, which together support what Boulding calls the econosphere, viewed as a material process involving the search, mining, and disposal of economically valueless by-products. The linear economy is currently also referred to as "Take – Make – Dispose" (Ekins *et al*., 2019). The current corn commodity cultivation system by farmers in Baradatu and Gunung Labuhan Subdistricts is a linear economy model, meaning the final process of corn cultivation activities is done by destroying the by-products by burning. The corn cultivation system is shown in Figure 3. In the Linear Economy Model shown in Figure 3, corn plant by-products are not utilized and are destroyed by burning by corn farmers.

Figure 3. Linear economy model in corn cultivation by farmers in baradatu and gunung labuhan subdistricts.

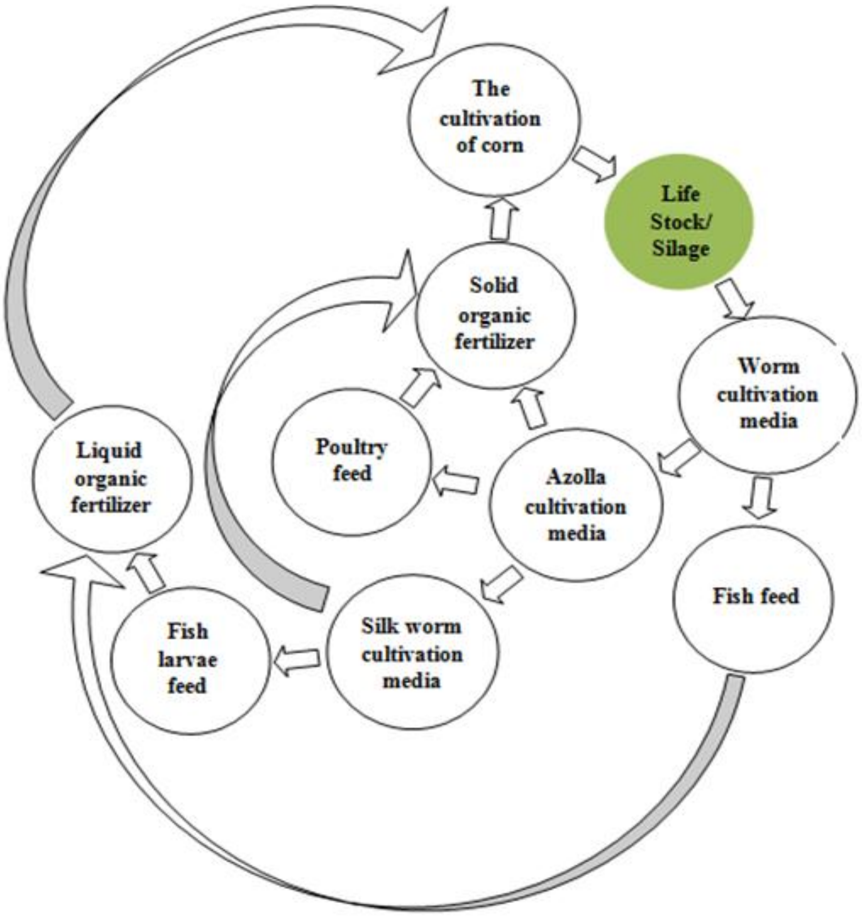

Figure 4. Circular economy model design for corn plant by-products. (Note: Green color represents the main product of the analysis, arrow indicates business development from derivative products)

4. CONCLUSION

Based on the research, it can be concluded that the selected alternative product using corn plant by-products, determined by the Exponential Comparison Method as Priority 1, is silage with an ECM score of 121,972,607. The developed Circular Economy Model offers many business opportunities by utilizing its derivative products as raw materials for other ventures such as worm cultivation, azolla cultivation, silk worm cultivation, freshwater fish breeding and rearing, poultry farming, processing of liquid organic fertilizer, and solid organic fertilizer.

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