Production of calcined eggshell: Process description and economic analysis

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Abstract. Adsorbents derived from eggshell (ES) have been proven to be effective for a variety of pollutants including organic and inorganic pollutants from different types of wastewater. Calcined eggshell (CES) had demonstrated a significant performance in which are on par with or even exceeds the commercially available adsorbents for phosphorus removal or recovery. This study aims to develop the process flow diagram for large scale production of CES with an overall economic analysis. A process flow diagram was developed starting from the transportation to storage of final product, CES. Calculation of process parameters were based on 1,000kg ES/day with 50% yield after the calcination process, generating about 475 kg CES/day. The total production cost was RM542,809.82 for producing 148, 675 kg of CES per annum. Based on these values, the cost of CES production per kg was estimated as RM3.58 or 0.76 USD. There is a great potential for CES in the future for the remediation of water and air pollutants.

1 Introduction

Eutrophication has always been one of the major issues in terms of water pollution. With the over-enrichment of nutrients leeching from multiple sources into water bodies, algal blooms have been severely affecting the sustainability of ecosystems and water bodies. To mitigate the issue of eutrophication, amount of phosphate found in water bodies must be strictly regulated and kept under the standards set by the Department of Environment. While phosphate in water sources is classified as one of the pollutants, it is also one of the important nutrients used in fertilizers for agricultural purposes. Most studies have been focusing on the removal of phosphate while limited studies have been conducted on the recovery of phosphate ions using waste green materials.

According to [1], approximately 90 million tonnes of chicken eggs were prospected to be produced annually while Malaysia has an annual production of about 642.6 thousand tonnes of chicken eggs which would yield around 70.7 thousand tonnes of eggshell (ES) waste. ES was found to have approximately 90 – 95% calcium carbonate, 1% magnesium carbonate, and calcium phosphate, respectively along with some organic compounds [2]. Although certain studies repurpose ES waste, the amount of waste that has been repurposed is still insignificant compared to the amount being disposed into landfills.

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Recent studies have shown the versatility and efficiency of calcined eggshell (CES) in the treatment of different pollutants from various sources [3-9]. According to [2] about 825,204 tonnes of ES waste have been generated by egg cracking factories in the year 2021. To cope with this issue, our recent studies have supported the previous statement that CES can recover phosphate from wastewater [11]. However, economic analysis for CES as an adsorbent has not been reported. Hence, this study aims to develop a process flow diagram for the upscale production of CES along with the economic analysis and marketability of the product to determine the total cost needed to manufacture CES from waste ES.

1.1 Process flow diagram development

Process flow diagram was developed based on [12]. Relevant processes were chosen accordingly based on lab scale experiments. Each process description was provided to identify yield values at various steps during the process and establish the required equipment for construction of the pilot plant. With the help of a process flow diagram, the manufacturing process is easier to understand while highlighting the possible errors that may occur during the design of a large-scale plant, avoiding extra costs to be incurred. With the energy and material balance, a preliminary estimation of fixed capital investment can be obtained.

1.2 Estimation of costs

Cost estimations were done based on quotations from online vendors during the process flow design. Transportation of materials and machinery, like augers, is encompassed as a part of the expenses of fixed capital investment. The sum of fixed capital investment was determined based on both equipment and capital cost as shown in Table 1. The design was done using an estimation of 1000 kg ES/day, operating 313 days annually with 2 operators with 8 working hours per day at a pay rate of RM 18/hr. Using the commercial rate of electricity tariff given by Tenaga National Berhad, each kilowatt-hour will cost RM 0.38 (Tenaga, 2022). Eq. 1 was used to calculate the operating power of each machinery in kilowatt-hours (kWh).

$$Power\ consumption\ (\text{kWh}) = time\ (\text{hr}) \times electricity\ consumption\ (\text{kW}) \quad (1)$$

Table 1. Estimated cost measurement method for pilot plant based on the percentage [8].

Services	Cost estimation	Services	Cost estimation
Equipment installation	25% of operating machinery	Contractor fee	1.5% of fixed capital investment
Instrumentation	6% of operating machinery	Contingency	5% of operating machinery
Piping and material transport	80% of operating machinery	Maintenance labor	15% of operating labor
Electrical installation	10% of operating machinery	Supervision	15% of operating labor
Building	12% of fixed capital investment	Fringe and benefits	16% of operating labor
Yard improvement	10% of operating machinery	Maintenance supplies	2% of operating machinery
Service facility	30% of operating machinery	Operating supplies	15% of maintenance supplies
Land	8% of operating machinery	General & administrative	2% of operating labor
Engineering and supervision	30% of operating machinery	Property insurance & tax	20% fixed capital investment
Construction expenses	1.5% of fixed capital investment	Depreciation	3% of building + 10% operating machinery

The percentage estimation was based on [12]. The total amount of annual fabrication and its expenditure were computed using Eq. 2 and 3 respectively.

$$Annual\ production\ =\ CES\ /day\ (kg)\ \times\ 313\ days/yr \tag{2}$$

$$Cost\ (per\ kg) = \frac{Total\ operating\ cost\ (RM)}{Total\ annual\ biochar\ production\ (kg)} \tag{3}$$

There are a few eggs-cracking industries and liquid egg production companies in Malaysia. For example, EggTech Manufacturing Sdn. Bhd. is one of the well-known companies in Malaysia for egg cracking. They produce about 0.5 tonnes of ES waste per day. Similarly, some other companies are willing to provide the ES waste for free for production. Thus, ES can be obtained without any extra cost. However, the cost of transporting the waste to the CES production factory is expected to be borne by the production company. After receiving ES wastes, it will be dried before storage and being sent to production line. To enable uniform burning and higher quality of adsorbent being produced, a grinder will be used to reduce the size of the ES to about < 90 µm into powder form. To convert it into a viable adsorbent, the calcination process will be done using a rotary kiln. The rotary kiln must be cooled down before retrieval of adsorbent post calcination with cooling process using a rotary cooler. At end of this production line, CES would be packed and stored accordingly.

2 Results

2.1 Simplified overall process flow

Figure 1 illustrates the simplified version of the overall flow for the manufacturing of CES with 1,000 kg of ES appropriated as feed amount per day. The main unit process of production system includes collection of feedstocks from factories, grinding, sieving, and calcination. ES wastes collected from factories will be dried completely before storage to prevent any moisture. Before the ES are calcined, a uniform and small particle size is required, hence the ES will be ground and sieved to obtain ES powder with particle size < 90 µm. Calcination of ES takes place in a rotary kiln to speed up the production rate of CES and ensure uniform heating is achieved. Before the adsorbent is packed and stored in final step, it is cooled to room temperature, hence a cooling system is essential to increase production efficiency of the entire system. The final step of CES production is to pack and store.

2.2 Process flow

Figure 1 portrays the detailed process flow diagram to produce CES. According to previous experience done in the lab scale testing, about 5% loss was observed after sieving while the yield after calcination will be about 50% of the feed to the rotary kiln. Hence, a feed of 1,000 kg of ES will yield about 475 kg CES as the final amount of adsorbent obtained.

Ideally, the moisture content of ES before calcination should be less than 5%. A rotary dryer that has a capacity of 1 tonne/hour is used to dry ES prior at 105°C. Upon drying about 3% loss is expected. Since the design is catered to handle approximately 1,000 kg of ES daily, long-term storage is also avoided in this case which is unfavorable for the production. Dried ES that was stored will be subjected to grinding and sieving with a ball mill and vibrating sieve with approximately 45 kW and 15 power rates, respectively. The ball mill has a capacity of 1.4 tonnes/hour, like the sieve. The 95% of the remaining feedstock (approximately 950 kg) after sieving will be fed into the rotary kiln with a burning capacity of approximately 1.04 tonnes/hour to undergo the calcination process at 800°C. Approximately 50% yield of CES is expected. Upon calcination, the product *i.e.* CES will be cooled down using a rotary cooler with a capacity of 2.5 tonnes/hour. Finally, CES is packed and stored for further use. It should be highlighted that some process ideas were adopted from [12]. The study had constructed a framework for the manufacture of activated carbon of another biomass.

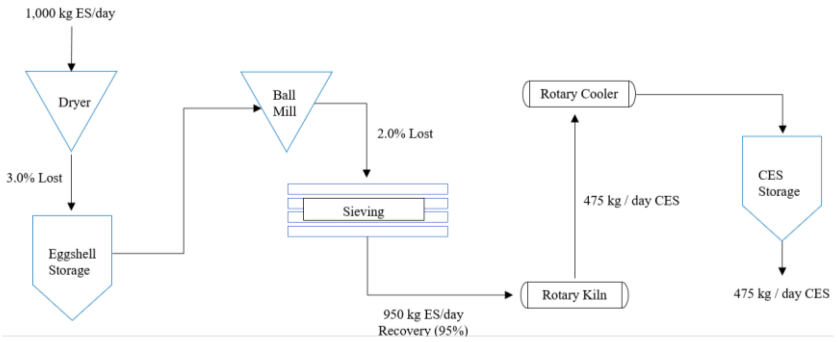

Fig. 1. Detailed process flow diagram of CES production.

2.3 Estimation of electricity consumption cost

The estimated cost, consumption of electricity, and power rating for each equipment is are tabulated in Table 2. The electric tariff for 200 kWh and below is rated at RM 0.38 and for every kWh more after 200 kWh is RM 0.44 by Tenaga Nasional Sdn. Bhd. [13] For the operations of moving the materials from one processing unit to another, conveyor belts are used. The rotary dryer will be operated for 1 hour, while the time for each conveyor belt to transfer the materials from one section to another is estimated to be a total of 2 hours. Subsequently, the ball mill and vibrating sieve are projected to be run for 1 hour, respectively. ES calcination process in a rotary kiln takes about 1 hour while the cooling process after calcination takes about 1 hour. All these are done in a day of production. Based on these operations, the electricity consumption for 313 operating days per annum was calculated as in Table 2. It is estimated that the cost of electricity usage will be approximately RM 9812.55.

Table 2. Electricity consumption and cost for CES production.

Items	Purpose	Power (kW)	Time (hr)	Total (kWh)	Cost (RM) (0.38/kWh)
Rotary Dryer	Drying eggshells	4	1	4	1.52
Conveyor Belt	Transport material	3	2	6	2.28
Ball Mill	Grinding	45	1	45	17.10
Vibrating Sieve	Sieving	1.5	1	1.5	0.57
Rotary Kiln	Calcination at 800 °C	18.5	1	18.5	7.03
Rotary Cooler	Cool down product	7.5	1	7.5	2.85
Total cost per day (RM)					**31.35**
Total cost per annum (RM) (313 operating days per annum)					**9,812.55**

*Electric Tariff (Tenaga National, 2022)

2.4 Capital cost estimation

Capital costs are expenses that are fixed and only spent once during the land purchasing, installation of equipment and electrical, construction of the building, engineering work supervision, equipment purchasing, etc. as vital part of establishing a manufacturing plant. To put it simply, it is the cost that is necessary to enable the entire project to operate. Table 3 summarises the cost of assets or equipment and the capital costs required.

According to Table 3, the total cost of asset purchase will be RM 93,345.00. The other costs incurred in Table 3 mentioning capital costs are done based on the site visit to a lime production facility to understand the requirements to establish a production facility. The major cost that is incurred will be the transportation of raw materials like piping and materials. Subsequent major costs will be the installation of equipment, supervision of engineering works, and service facilities. For cases of emergency, a contingency cost was included. Hence, the total equipment and other capital costs are estimated as RM317,770.56.

Table 3. Estimated equipment and other capital cost for CES production.

Asset Cost	(RM)	Capital Cost	(RM)
Rotary Dryer	4,200.00	1 Tonne Lorry	20,000.00
Conveyor Belt	28,020.00	Equipment and electrical installation	32,670.75
Ball Mill	11,675.00	Instrumentation	5,600.70
Vibrating Sieve	7,400.00	Piping and material transport	74,676.00
Rotary Cooler	18,700.00	Buildings and yard improvements	20,535.90
		Land and service facilities	35,471.10
		Engineering and supervision	28,003.50
		Construction and contractor’s fee	2,800.36
		Contingency	4,667.25
Total equipment cost (RM)	**93,345.00**	**Total other capital costs (RM)**	**224,425.56**

2.5 Operating cost estimation and summary

The operational cost was estimated based on the production line. Based on 475kg of CES produced per day, it can be concluded that about 148,675 kg of CES can be obtained per year from 313 working days. Table 4 summarizes the details of annual operational costs to produce CES. The cost for the utility of electricity is adopted from Table 2. Fees for operating labor were calculated based on working hours and fringe benefits are the compensation for services that is more than the regular pay rate of the employee. Supplies fees include materials that are regularly consumed during the business operation like computer supplies, office supplies, etc. while general works include those that are not part of the production line such as clerks and secretaries along with the insurance and tax for plant operation. A depreciation value is added as a value estimation of buildings and assets. Hence, it is deduced that the annual operational cost of CES is found to be approximately RM215,039.26 for the annual production of 148,675 kg of CES. Table 4 also outlines the summary of expenses required to establish and operate the pilot plant. The sum of fixed capital investment and operating cost was RM532,809.82 and the cost of CES production per kg was estimated as RM3.58.

Table 4. Estimated annual operating cost and cost summary for CES.

Description	Annual operating costs (RM)	Description	Cost summary (RM)
Raw material (eggshell)	0.00	Total capital cost (a)	317,770.56
Utilities (electricity)	9,812.55	Total operating cost per annum (b)	215,039.26
Labour (Operating, maintenance, supervision, and fringe benefits	131,610.24	Total production cost (a + b) = c	532,809.82
Maintenance and operating supplies	2,146.94	CES production per annum (kg) (d)	148,675
General works	56,358.53		
Lorry Operation	15,111.00		
Total annual operating cost	**215,039.26**	**Cost of production (RM/kg) (c/d)**	**3.58**

2.6 Cost comparison

Table 7 shows the price comparison in USD between calcium oxide made from different raw materials. Current work successfully developed a cost-effective adsorbent from waste material which only costs about USD0.76/kg compared to limestone-based starting material. The lower price of CES could be attributed to the preparation process that does not require any extra chemical or activation process. Moreover, CES can be reused as a soil conditioner after post-treatment. While the study by [14] had a lower cost of production, no details of calculation were justified in the study.

Table 5. Comparative cost of other commercial biochar and the current study.

Raw material	Material	Region	Cost (USD/kg)	Reference
Eggshell	Calcium oxide	Korea	0.30	[14]
Limestone	Calcium oxide	Malaysia	0.85	[15]
Limestone	Calcium oxide	China	50.00	[16]
Limestone	Calcium oxide	Malaysia	8.52	[17]
Eggshell	Calcium oxide	Malaysia	0.76	This study

3 Conclusions

A simple and detailed process flow diagram was drafted for the mass production of CES through calcination. From the diagram, the cost had been predicted for each process for the production per annum and fixed capital investment. Larger pilot plants would make it more economical to produce biochar as a larger amount can be produced to offset the cost of production due to the upsizing of plant and further increase the profitability of biochar. This study-considered the daily feedstock to be 1,000 kg of ES for production. The cost for the entire CES production plant was found to be RM3.58 or USD0.76 per kg of CES. Cost analysis had sufficiently proved that CES is economical with prospective marketability when compared to other studies. Through the commercialization of CES as an adsorbent, a sustainable element can be promoted in both wastewater treatment industry and waste management industry through recycling ES and transforming it into a value-added product. Moreover, comparing the commonly found biochar in the market, CES has a very significant advantage in terms of economic value as well as in the environment. Hence, CES is feasible to be commercialized as an adsorbent to adsorb phosphorus from various types of wastewater.

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References

1. W. Ahmad, S. Sethupathi, Y. Munusamy, and R. Kanthasamy. Valorization of raw and calcined chicken eggshell for sulfur dioxide and hydrogen sulfide removal at low temperature. *Cat.,* **11(2)**, 295 (2021). https://doi.org/10.3390/catal11020295.
2. M. Baláž. Ball milling of eggshell waste as a green and sustainable approach: A review. *Adv. in coll. and inter. sci.*, **256**, 256-275 (2018). https://doi.org/10.1016/j.cis.2018.04.001.
3. D. Chen, X. Xiao, and K. Yang. Removal of phosphate and hexavalent chromium from aqueous solutions by engineered waste eggshell.*RSC adv.*, **6(42)**, 35332-35339 (2016). https://doi.org/10.1039/C6RA05034D

4. X. Liu, F. Shen, and X. Qi. Adsorption recovery of phosphate from aqueous solution by CaO-biochar composites prepared from eggshell and rice straw. *Sci. of the tot. environ.*, **666**, 694-702 (2019). https://doi.org/10.1016/j.scitotenv.2019.02.227
5. J.H. Park, A.Y. Choi, S.L. Lee, J.H. Lee, J.S. Rho, S.H. Kim, and D.C. Seo. Removal of phosphates using eggshells and calcined eggshells in high phosphate solutions. *Appl. Biol. Chem.*, **65(1)**, 75 (2022). https://doi.org/10.1186/s13765-022-00744-4
6. S. Pérez, J. Muñoz-Saldaña, N. Acelas, E. and Flórez. Phosphate removal from aqueous solutions by heat treatment of eggshell and palm fiber. *Jour. of Environ. Chem. Eng.*, **9(1)**, 104684 (2021). https://doi.org/10.1016/j.jece.2020.104684
7. J. Torit, and D. Phihusut. Phosphorus removal from wastewater using eggshell ash. *Environ. Sci. and Pollut. Res.*, **26(33)**, 34101-34109 (2019). https://doi.org/10.1007/s11356-018-3305-3
8. C. Xu, R. Liu, Q. Tang, Y. Hou, L. Chen, and Q. Wang. Adsorption Removal of Phosphate from Rural Domestic Sewage by Ca-Modified Biochar Derived from Waste Eggshell and Sawdust. *Wat.*, **15(17)**, 3087 (2023). https://doi.org/10.3390/w15173087
9. Y. Zhang, H. Li, Y. Zhang, F. Song, X. Cao, X. Lyu, Y. Zhang, and J. Crittenden. Statistical optimization and batch studies on adsorption of phosphate using Al-eggshell. *Ads. Sci. & Tech.*, **36(3-4)**, 999-1017 (2018). https://doi.org/10.1177/0263617417740790
10. T.A. Ahmed, L. Wu, M. Younes, and M. Hincke. Biotechnological applications of eggshell: recent advances. *Front. in Bioeng. and Biotech.*, **9**, 675364 (2021). https://doi.org/10.3389/fbioe.2021.675364
11. S.Y. Tan, S. Sethupathi, K.H. Leong, and T. Ahmad. Mechanism and kinetics of low concentration total phosphorus and reactive phosphate recovery from aquaculture wastewater via calcined eggshells. *Wat. Air Soil Pollut*, **233(11)**, 445 (2022). https://doi.org/10.1007/s11270-022-05905-1
12. C. Ng, W.E. Marshall, R.M. Rao, R.R. Bansode, J.N. and Losso. Activated carbon from pecan shell: process description and economic analysis. *Ind. crops and prod.*, **17(3)**, 209-217 (2003). https://doi.org/10.1016/S0926-6690(03)00002-5
13. Tenaga Nasional Berhad. PRICING & TARIFFS: Industrial Tariffs (2024). Available at: https://www.tnb.com.my/commercial-industrial/pricing-tariffs1/
14. H.J. Choi. Assessment of the adsorption kinetics, equilibrium, and thermodynamic for Pb (II) removal using a low-cost hybrid biowaste adsorbent, eggshell/coffee ground/sericite. *Wat. Environ. Res.*, ***91*(12)**, 1600-1612 (2019). https://doi.org/10.1002/wer.1158
15. Shopee.com, n.d. *Calcium Oxide 氧化钙 - 生石灰 /CaO -Food/Cosmetics Grade Burnt Lime*. *Shopee.com.my*. Available at: https://shopee.com.my/product/5488153/1092509879?d_id=128b0&uls_trackid=4vp37l1q00rq&utm_content=mxyRkTzNuRpVTtuWjnYakgJNUUX (Access:14 May 2024).
16. Alibaba.com. High quality calcium oxide powder Cao Cas 1305-78-8 factory calcium oxide price for Leather. Available at: https://www.alibaba.com/product-detail/High-Quality-Calcium-Oxide-Powder-CaO_1600651410464.html
17. Take It Global. Calcium Oxide Takeitglobal.my (2024). Available at: https://takeitglobal.my/products/calcium-oxide-cao-cosmetics-grade?variant=30980502093929&currency=MYR&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic&srsltid=AfmBOor8p2K3_WdHi4cIel756N0Nq_9FtGJ0DKTPtbQs-gLqhSLs4Zarxag