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Abstract
The worldwide decline and overexploitation of ocean fisheries stocks had provided an incentive for the rapid growth of aquaculture. The aquaculture industry has been recognized as the fastest-growing food production system globally, with a 10% increase in production per year and is one of the most reliable and sustainable growth markets for manufactured feeds. Extrusion technology has been extensively used in the modern aquatic feed manufacturing, due to nutritional, physical properties improvements and cost effectiveness of feeds. Cost related to aquatic feed remains the biggest challenge, especially for small-scale producers. In order to understand costs and potential breakeven points, a single screw extruder and three different production scenarios (0.2, 2 and 20 t/day) throughput were used to develop techno-economic models for small-scale producers of extruded aquatic feeds. The results show annualized capital costs decreased as production capacity increased. Thus, aquatic feed producers could use this tool to evaluate annual costs and benefits to determine processing economics. Producers will have to consider the ingredients used, though, as raw ingredients constitute the greatest cost for the production of feeds.

Keywords
Aquaculture, extrusion, techno-economic analysis, economic cost analysis, aquatic feeds

Disciplines
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Techno-economic Analysis (TEA) of Extruded Aquafeeds

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Abstract

The worldwide decline and overexploitation of ocean fisheries stocks had provided an incentive for the rapid growth of aquaculture. The aquaculture industry has been recognized as the fastest-growing food production system globally, with a 10% increase in production per year and is one of the most reliable and sustainable growth markets for manufactured feeds. Extrusion technology has been extensively used in the modern aquatic feed manufacturing, due to nutritional, physical properties improvements and cost effectiveness of feeds. Cost related to aquatic feed remains the biggest challenge, especially for small-scale producers. In order to understand costs and potential breakeven points, a single screw extruder and three different production scenarios (0.2, 2 and 20 t/day) throughput were used to develop techno-economic models for small-scale producers of extruded aquatic feeds. The results show annualized capital costs decreased as production capacity increased. Thus, aquatic feed producers could use this tool to evaluate annual costs and benefits to determine processing economics. Producers will have to consider the ingredients used, though, as raw ingredients constitute the greatest cost for the production of feeds.

Keywords: aquaculture, extrusion, techno-economic analysis, economic cost analysis, aquatic feeds

1. Introduction

The aquaculture industry has been recognized as the fastest-growing food production sector globally, with a 10% increase in production per year (Townsley, 2013), fuelled by a combination of population growth, decline or stagnation of ocean fisheries stocks, increased global demand, rising income, urbanization and increased awareness of the nutritional benefits of fish (Naylor et al., 2000; FAO, 2014). It has been reported by Lapere (2010) that the global declining of fish catches concurred with the increasing demand for fish and this made the prospect of aquaculture sectors very bright. In 2015, aquaculture-farming production attained an all-time high 106million metric t and growing at an average annual rate of 6.6 percent since 1995 (FAO, 2017). Currently, aquaculture accounts for over one-fourth of all fish consumed by human (Naylor et al., 2000). According to the Food and Agriculture Organization of the United Nations (FAO), each year aquaculture sector contributes over 19 million metric t of fish to the world's fish supply chain (FAO, 2012). To meet rapidly growing demand of aquaculture production, global aquatic feed production is expected to reach 71.0 million metric t by 2020 (FAO, 2012). Fish feed manufacturing is considered one of the most reliable and sustainable industry in feed production (Rosentrater et al., 2009a).

Extrusion technology has been extensively used in the modern fish feed manufacturing (Sørensen et al., 2009), due to nutritional and physical property improvements of feeds such as in the overall feed quality, increasing durability and water stability of feeds, as well as cost effectiveness of finished feeds (Davis & Arnold, 1995; Cheng et al., 2003). In aquaculture farming, feed costs account for 30 % and 60% of the total production costs (Shipton & Hasan, 2013). Although this technology is well accepted in the feeds industry, there are still few published papers on cost and benefits, especially for small-scale feed producers. Thus, the objective of this study was to conduct techno-economic analyses of small-scale extruded aquatic feeds.

1.1 Extrusion Processing

Extrusion technologies have an important role in the foods, and feed industries as manufacturing processes (Guy, 2011). Extrusion is regarded as one of the most versatile and energy-efficient processes in food and feed production (Dziezak, 1989). Extrusion cooking is defined as a high-temperature-short-time (HTST) cooking process, which involves the cooking of ingredients in the extruder barrel, by a combination of high pressure, heat and friction. Materials exit through a small die which is designed to produce highly expanded, low-density products with unique physical and chemical characteristics (Robinson, 1991; Pansawat et al., 2008). Extrusion cooking has gained popularity in aquatic feed manufacturing due to potential improvements in feed quality, increased versatility, high productivity, low cost and energy efficiency (Previdi et al., 2006). Moreover, extrusion cooking is environmentally friendly (produces little process effluents) and can be operated continuously with high throughput (Guy, 2011). Most of the fish feeds produced in the US and other developed countries are manufactured almost exclusively using extrusion technology (Cheng et al., 2003). According to Shipton & Hasan (2013) fish feed costs and efficiencies can significantly improve by using simple extruders.

Additionally, extrusion process can also improve the final product in terms of durability, digestibility, and palatability, increase animal performance, and destroy pathogenic microorganism in the feed (Ayadi et al., 2011; Rosentrater et al., 2009b). Besides the economic benefits, chemical and structural (physical) transformations occurring during extrusion cooking, such as gelatinization and expansion of the starches, formation of lipid complexes, enzyme inactivation, denaturation of anti-nutritional factors, and degradation reactions of pigments (Ding et al., 2005), all at which have both physical and nutritional benefits (Cheng et al., 2003). In extrusion cooking, the quality of the final product depends mainly on the extruder type, die geometry, screw speed and configuration, feed moisture and composition, feed particle size, feed rate, and temperature profile in the barrel (Ding et al., 2005; Pansawat et al., 2008).

1.2 Types of Extrusion

Generally, extrusion is categorized according to screw types; single screw and twin-screw extruders. Single screw extruders are an attractive option for many applications due to low capital investment, low manufacturing cost, low maintenance, simplicity in design, and straightforward operation (Kim & Kwon, 1996). A typical single screw extruder (Figure 1) is usually comprised of three main zones: feed, metering, and compression, with a die for shaping (Previdi et al., 2006). It relies on drag flow to move the material down the barrel and develops pressure at the die (Kelly et al., 2006). Material enters from the feeder and moves in a channel toward the die when a screw rotates inside the barrel (Kim & Kwon, 1996). Moreover, twin-screw extruders are classified according to the direction of screw rotation as either counter-rotating or co-rotating (Ayadi et al., 2011). Advantages of the twin-screw extruders over the conventional single-screw extruders are better control of residence time, and more uniform distribution of shear within the material (Kim & Kwon, 1996). Twin-screw extruders can process materials with different moisture contents and different viscosities (Hsieh et al., 1990).

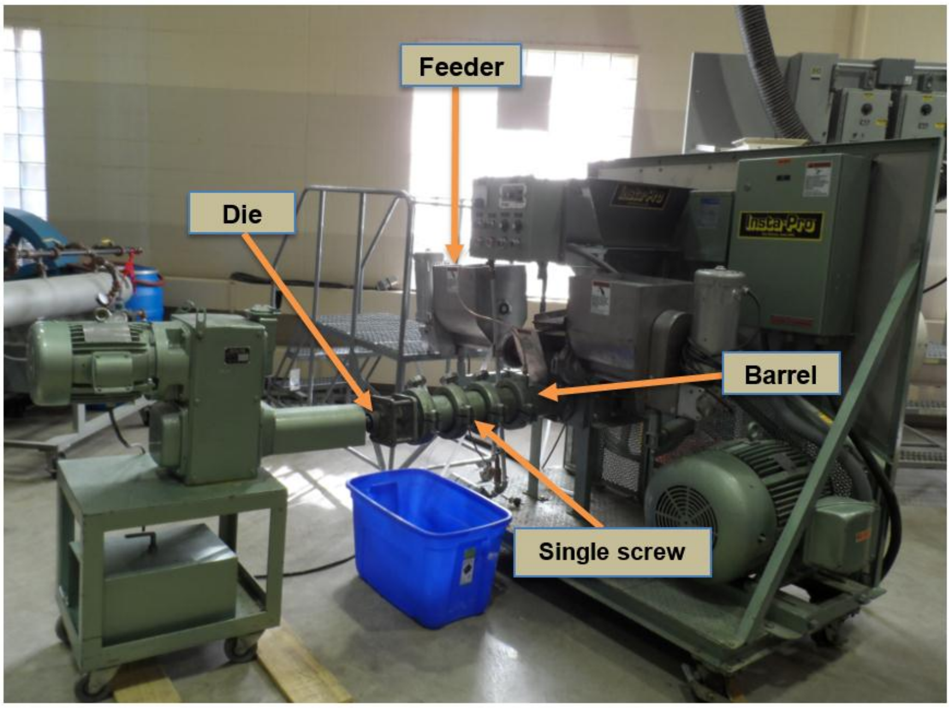

Figure 1. Example of a commercial scale single screw extruder

In addition, twin-screw feed rates are independent of screw speed and not influenced by pressure flow caused by restriction at the die (Altomare & Ghossi, 1986). Also, twin-screw extruders can have larger heat transfer areas, larger outputs, more positive conveying, shorter residence times, better mixing, and less wear and tear compared to single-screw extruders (Ayadi et al., 2011). In aquatic feed manufacturing, twin-screw extruder is often favoured over single screw extruder due to their abilities to handle wet materials, oily, or sticky ingredients (Cheng et al., 2003), and viscous materials with different levels of composition (protein, starch, lipids, and fiber) over a wide range of particle sizes (Chevanan et al., 2007). Additional advantages of twin-screw is their abilities to produced floating feeds, which may, prevent excess feeding and are easy to handle, and hence are often preferred by aquaculture farmers to sinking feeds (Chang & Wang, 1999). Furthermore, twin-screw extruders can handle feed recipes up to 22% fat compared to 12-17% for convectional single-screw extruders (Cheng et al., 2003). In this study, a single screw extruder was selected over twin-screw since been the common extruders used by most of small-scale feed producers due to lower capital investment and easy to handle. The objective of this study was to examine production costs, and thus breakeven points, for a single screw extruder, using a prototype diet mix.

2. Materials and Methods

In order to correctly model a prototype system and prototype feed blend (Table 1), pilot-scale extrusion was performed using a single-screw extruder (Insta-Pro, model 500, Des Moines, Iowa) with a 45 mm diameter screw and a 20:1 length to diameter (L/D) ratio. Feed blends were manually fed into the extruder. The extruder was connected to a 7.5 HP motor and screw speed was set at 600 RPM (Rosentrater et al., 2009a). The mass flow rate was determined by collecting feed samples at 30-second intervals during the extrusion process and weighting the samples on an electronic balance (Rosentrater et al., 2005b). Mass flow rates recorded ranged from 0.089 to 0.095 kg/s. The temperatures of the die and of the resulting pellets produced were recorded after every two minutes using an infrared thermometer and were 53 ± 5 ℃ for the die and 63 - 70 ℃ for the extrudates. A circular die plate (with multiple 3 mm holes, Figure 2) was attached to the extruder. The overall process flow is shown in Figure 3; and Figure 4 illustrates the resulting extruded pellets. These processing data were then subsequently used to model the production costs for this prototype system and prototype blend.

Table 1. Prototype feed blend used in this study and associated costs. Scenarios are defined in Table 3.

Ingredient	Total mass (t)	Inclusion level (%)	Material cost ($/t)	Scenarios ($/y) I	II	III
Menhaden fish meal	0.2000	40.00	800	16,000	160,000	1,600,000
Soy protein concentrate	0.0950	19.00	800	7,600	76,000	760,000
Corn starch	0.0594	11.88	550	3,267	32,670	326,700
Wheat flour	0.0750	15.00	400	3,000	30,000	300,000
Corn gluten meal	0.0150	3.00	750	1,125	11,250	112,500
Menhaden fish oil	0.0355	7.10	720	2,556	25,560	255,600
Soy lecithin	0.0050	1.00	1,100	550	5,500	55,000
Carboxymethyl cellulose	0.0100	2.00	3,000	3,000	30,000	300,000
Choline chloride	0.0300	0.60	900	270	2,700	27,000
Stay-C	0.0010	0.20	500	50	500	5,000
Vitamin Premix	0.0006	0.120	800	48	480	4,800
Mineral Premix	0.0005	0.100	500	25	250	2,500
Total mass per diet	0.50	100		37,491	374,910	3,749,100

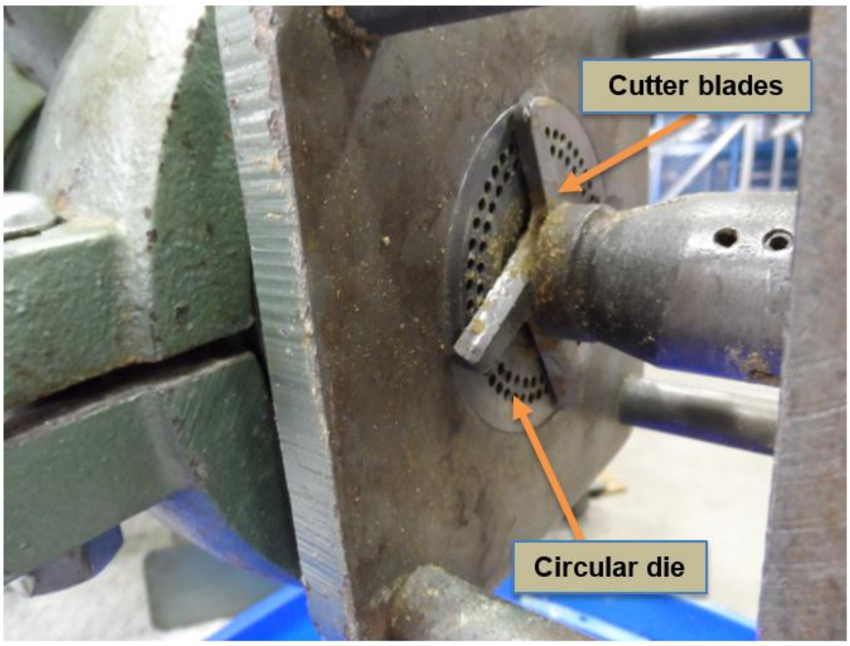

Figure 2. Example of a circular extruder die with multiple die openings

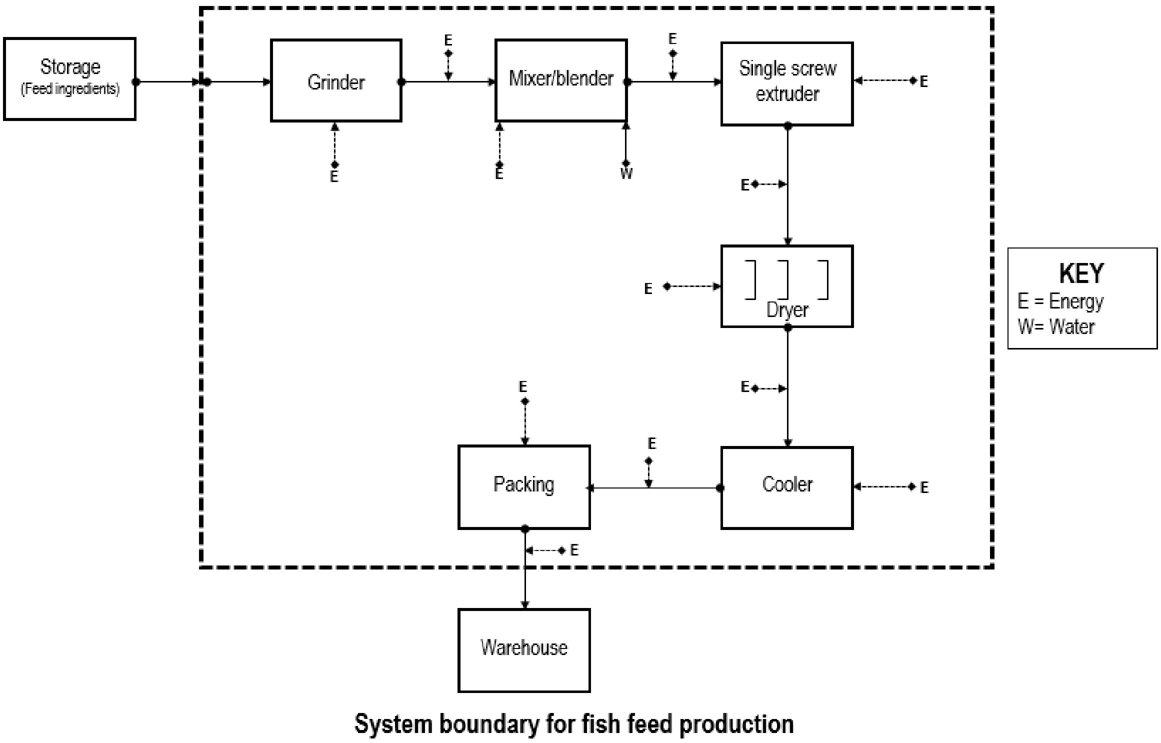

Figure 3. Process flow diagram used to model feed production in this study

Figure 4. Example of extruded fish feeds.

2.1 Techno-economic Analysis

Techno-economic analysis (TEA) is defined as a systematic analysis used to evaluate the economic feasibility aimed to recognize opportunities and threats of projects, taking into account the capital, variable (operational), and fixed costs (Simba et al., 2012), as well as benefits. Fixed and annual operating costs are critical parameters in TEA and are key factors for cost estimation, project evaluation, and process optimization (Marouli & Maroulis, 2005). The TEA in this study was conducted using a spreadsheet (MS-Excel) to determine the total annual cost of extrusion processing for the prototype aquatic feeds.

Economic cost analysis calculations were based on the assumptions made in Table 2 and the processing data collected in the pilot plant. Costs were divided into capital, variable, and fixed costs. Equipment costs, installation/electrical work, process spouting/piping costs, and the engineering/construction costs were included in the capital cost category, while utilities (electricity and water) costs, feed ingredient costs, labor costs, maintenance and repair costs, raw ingredient freight charges, delivery fuel expenses, and other miscellaneous supply costs were categorized as variable costs. Fixed costs are those costs associated with depreciation, insurance, interest, overhead, and taxes. In this study, three feed production rates (0.20 t/day, 2 t/day, and 20 t/day) were evaluated for the techno-economic analysis (Table 3).

Table 2. General processing assumptions used to model extrusion

Bulk feed storage requirements	Equal to daily processing capacity
Delivery radius	0 to 160 km
Delivery truck fuel consumption	3 km/L
Yearly operational hours	2000 h
Bin service life	15 y
Labor	10 $/h + 25% benefits
Daily operation hours	8 h
Equipment service life	15 y
Electricity use	Lighting and motor power
Electricity use	Motor speed reductions of 75%

Table 3. Production scenarios used to conduct techno-economic modelling

	I	II	III
Daily storage capacity - t/day	0.2	2	20
Yearly storage rate (G) - t/y	50	500	5,000
Interest rate (I)	5%	5%	5%
Daily operation hours (OH) - h/day	8	8	8
Operation hours (OH) - h/y	2000	2000	2000

3. Results and Discussion

3.1 Capital Costs

Capital costs are the most important cost in plant establishment and construction; they are the initial investment cost put into the plant. In this study, the capital costs for each scenario were calculated based on the summation of the total initial equipment costs, building costs, and engineering/construction work costs (Wood et al., 2014). The equipment costs were obtained from different manufacturers/suppliers. Results show that annualized capital cost per t decreased as the production rate increased from 1426.45 $/t, 166.43 $/t to 52.27 $/t for scenarios I, II, and III, respectively, as shown in Figure 5. As mentioned by Marouli & Maroulis (2005) the key factor to reduce costs is to increase the size of the plant. Generally, the capital (equipment and building) costs decrease as the size of the plant increases.

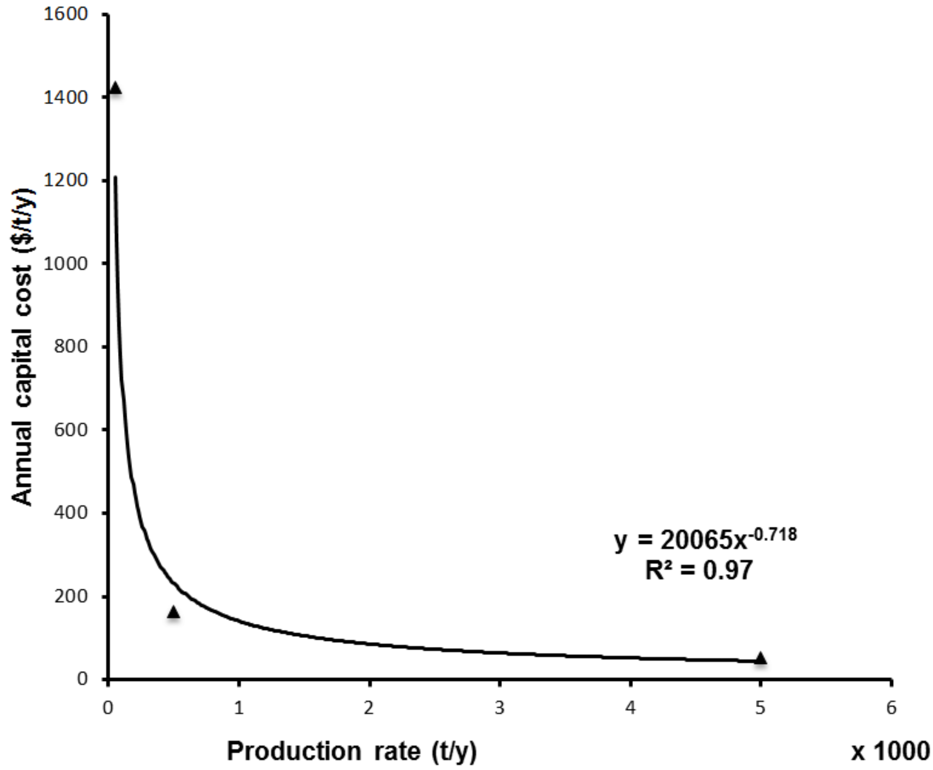

Figure 5. Annualized capital costs as determined by TEA

3.2 Labor Costs

The annual variable costs of feed processing plant include the costs associated with labor, utilities, ingredients, maintenance and repair, and other facilities cost required for daily operation. In all scenarios, variable costs had the greatest impact on the total operational cost. The cost of labor was calculated based upon the number of workers, total annual operational hours and estimated wages per hour. Total annualized labor cost per t for all scenarios was estimated to be $86.49 /y. This result indicates that labor is the second largest contributor to the variable cost with 9.93 % of the overall variable costs (Figure 6).

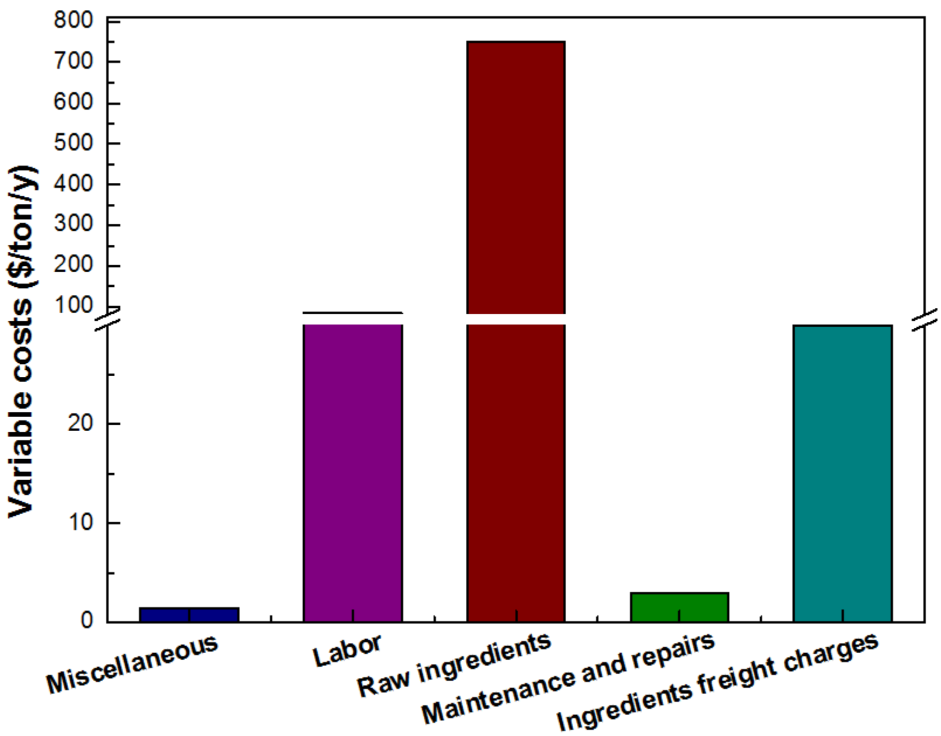

Figure 6. Annualized variable costs according to scale

3.3 Utility Costs

The utilities used in this study were electricity and water. The results show that the costs of utility increased as the production rate increased. Electricity cost is important in feed manufacturing; it includes costs for lighting and powered machineries such as extruders, mills, and conveyors. Electricity contributes the largest component of utility costs, approximately 78.58% of the total annualized utility, for all production scenarios. The annualized cost of water per t in all production scenarios were estimated to be $111/t, equal to 21.42% of the total utilities cost and overall utility contribute 1.07% of the overall variable costs.

3.4 Materials (ingredients), Maintenance, and Repair Costs

Feed ingredient costs were determined based on different supplier prices of materials per metric t. As expected the annual costs of materials increased as production rate increased. It can be seen that the costs of materials had the greatest impact on the overall variable costs (average of 86.11%) as shown in Figure 6. The price of Menhaden fishmeal was higher compared to other ingredient costs. The maintenance costs were determined as 3% of the capital investment costs and contributed 0.34% of the overall averaged variable costs. Other variable costs are shown in Figure 6 and Table 4.

Table 4. Annualized variable costs as determined by TEA.

Variable costs ($/t/y)	
Electricity	0.07
Water	0.02
Labor	86.49
Raw ingredients	749.82
Maintenance and repairs	3.00
Miscellaneous supplies	1.00
Others	0.25
Ingredient freight charges	30.00
Delivery fuel expenses	0.01

3.5 Fixed Costs and Depreciation

Fixed costs are constant costs and independent of production rates (Pearlson, 2011). It includes costs of depreciation, insurance, interest, overhead, and taxes. Depreciation was calculated using the straight-line method over the estimated service life of the assets. Depreciation is a non-cash deduction that occurs in the financial (profit and loss) report. Different equipment in feed production depreciates at different rates, and there are different methods of calculating depreciation. In this study, depreciation was calculated using the straight-line method over the estimated life services of the assets (equation 1) for simplicity:

$$\text{Straight line depreciation} = \frac{\text{Assets (Purchase Price} - \text{Salvage Value)}}{\text{Estimated useful life}} \quad (1)$$

Since assets cost increases with increased capital investment, thus, depreciation values increased as production rate increased, and annual depreciation calculated in this study were \$892.24, \$1214.44, and \$5730.61 for scenario I, II and III, respectively. Figure 7 show annualized fixed costs of three-production scenarios.

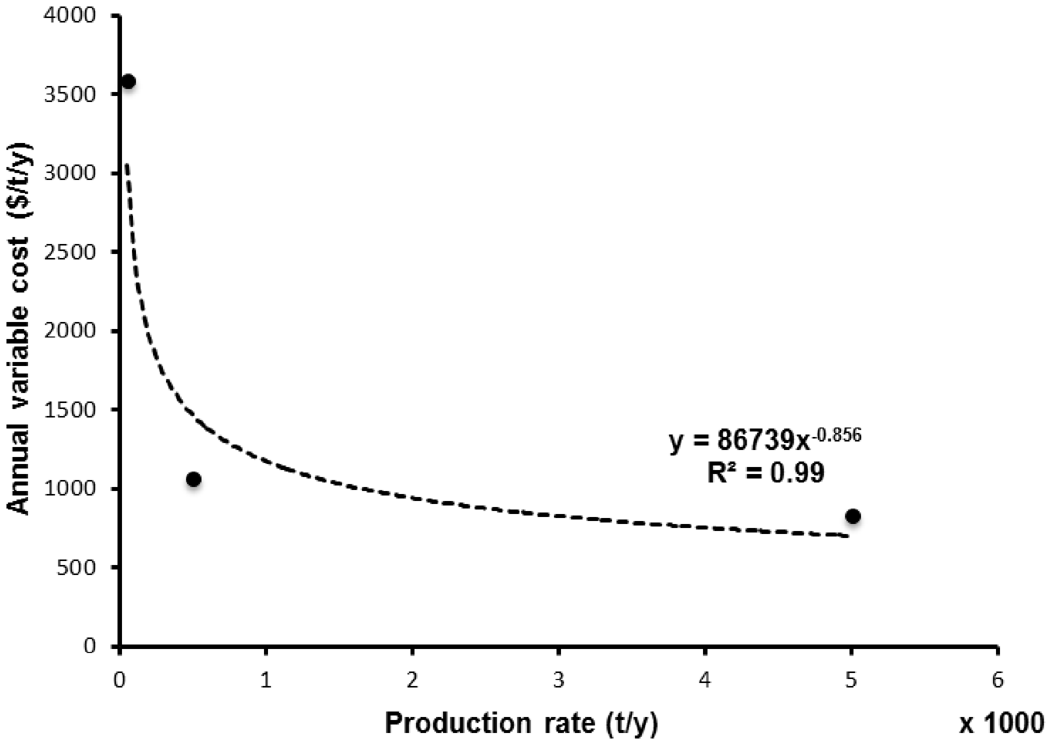

Figure 7. Annualized variable costs as determined by TEA.

3.6 Insurance, Interest, Overhead, Tax Costs and Total Annualized Costs

Insurance was calculated by multiplying 0.00462 (Davis et al., 2011) with the sum of initial equipment costs and building cost, insurance costs are proportional with the production rate, as rate increased from 50 t/y to 5000 t/y, insurance also increased from \$307.95/y to \$1128.54/y. Interest costs were related to capital investments. In this study, a 5% interest rate was used. The costs were determined by equation (2). Interest contributed 62% of the total fixed costs.

$$\text{Interest (\$/y)} = \left(\frac{\text{I}}{100}\right) * \text{(Initial equipment costs + building costs)} \quad (2)$$

Where I = interest rate (5 %)

Like other variable costs, overhead, and taxes increased as the capacity increased. Overhead was calculated by multiplying the production rate by 0.16 (Rosentrater, 2013). On the other hand, taxes were calculated as 0.35% (Rosentrater, 2013) of the total capital costs. The total annualized fixed cost decreased as production rate increased as shown in Figure 8. Total cost including both capital, variable, and fixed costs. As expected, the total annualized costs per unit t decreased as the production rate increased (4906.64 \$/t/y, 1219.05 \$/t/y and 873.39 \$/t/y) as shown in Figure 9.

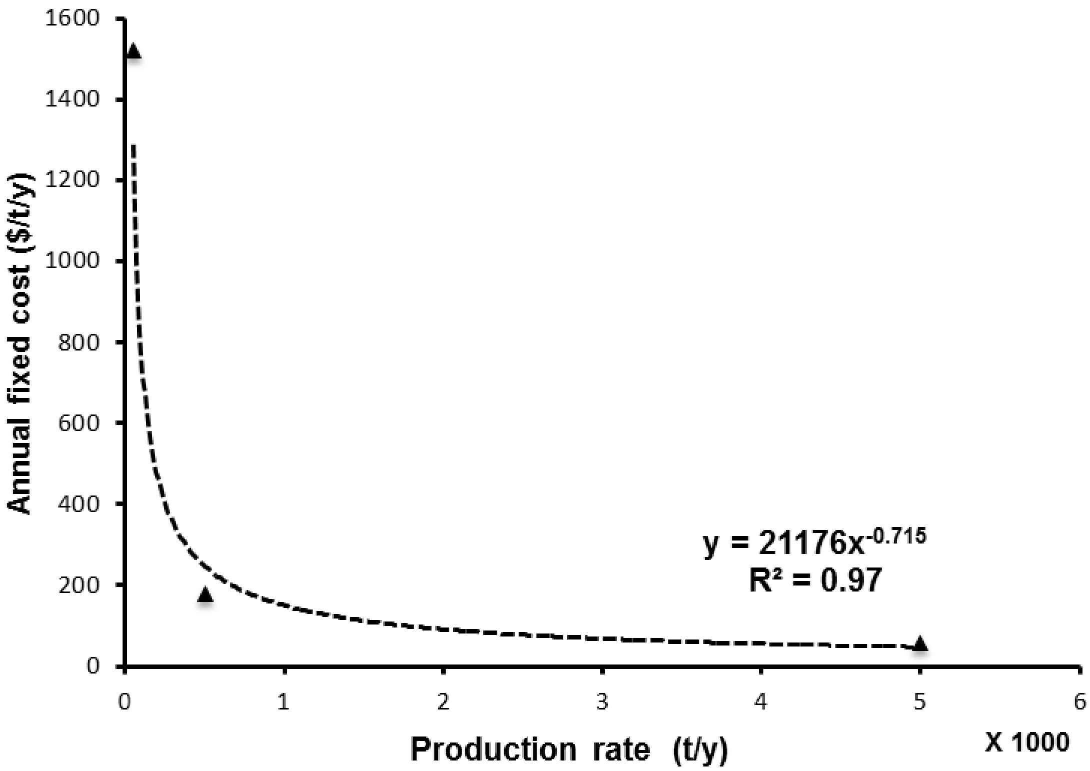

Figure 8. Annualized fixed costs as determined by TEA

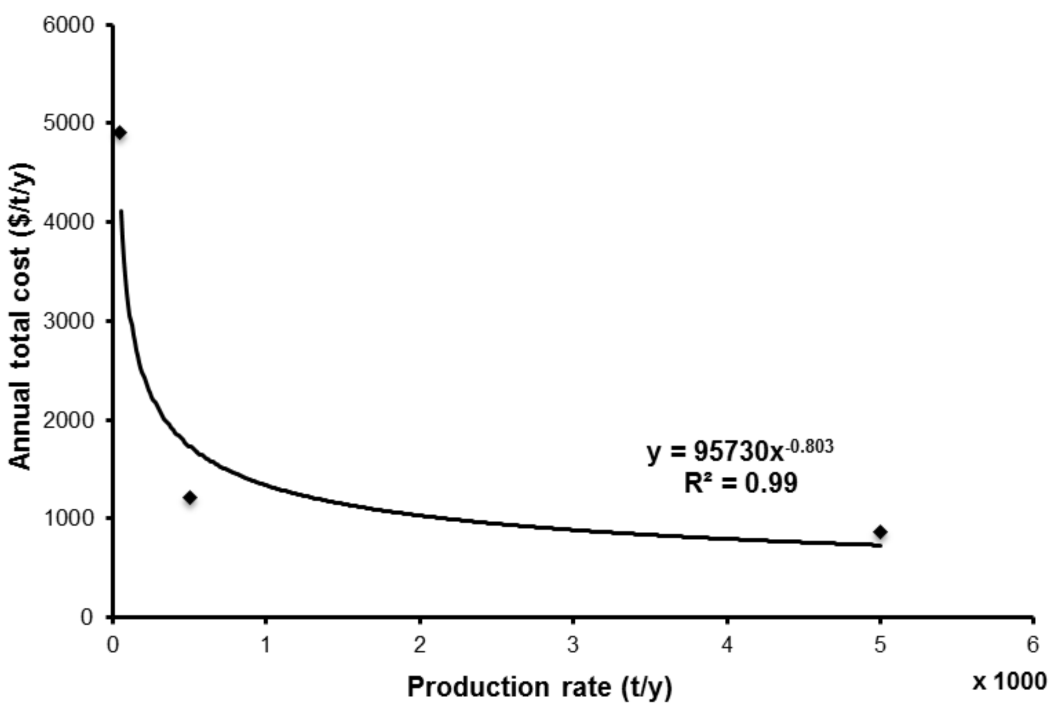

Figure 9. Annualized total costs as determined by TEA. In order for the production to break even, sales price much be equal to the annual total costs. In order to make profit, sales price must be greater than annual total costs

4. Conclusions

Decline of world fish capture has provided opportunities for aquaculture sectors and creates an open market for aquatic feeds. Extrusion technology has been broadly used in feed manufacturing due to high quality and cost effectiveness of aquatic feeds. However, factors such as product cost analysis limit feed production for small-scale producer, thus, techno-economic analysis could be a useful tool for small scale extruded feed producers to analyze the production costs, and the results show as production capacity increased overall production costs of feeds decreased. The greatest cost category was raw ingredients used, so it is incumbent upon producers to optimize the feed blends used for specific fish species. Labor was the second greatest cost category. Consequently, in order to small scale fish feed producers to break even, or make a profit, both operations and feed blends must be considered. Opportunities exist for small feed producers, but they must be judicious in their implementation.

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