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Sustainability assessment of salmonid feed using energy, classical exergy and eco-exergy analysis

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ABSTRACT

Reduction of the environmental impact of feed products is of paramount importance for salmon farming. This article explores the potential to compare three thermodynamically based ecological indicators. The environmental impact of partial replacement of fish meal (FM) and fish oil with alternative ingredients was investigated using energy, classical exergy and eco-exergy analysis. Seven hypothetical feeds were formulated: one with high levels of FM and fish oil, four feeds based on plant ingredients, one containing krill meal, and one based on algae-derived products. Analysis included cultivation of crops and algae, fishing for fish and krill, industrial processing of these ingredients and production of complete fish feed. Because most harvested products are refined in multiple product outputs that have good value to society, two scenarios were compared. In the base case scenario, no allocation of co-products was used and all the environmental costs were ascribed to one specific co-product. Co-product allocation by mass was used in the second scenario; this is considered to be the preferred scenario because it accurately reflects the individual contributions of the co-products to the environmental impact of the feed products. For this scenario, the total energy consumption for a fish-based diet was 14,500 MJ, which was similar to a krill diet (15,600 MJ), about 15–31% higher than plant-based diets, and 9% higher than an algae diet. Substituting FM and fish oil with alternative ingredients resulted in minor changes in total classical exergy degradation (2–16% difference). The calculations based on energy only consider the energy conservation based on the First Law of Thermodynamics, whereas those based on classical exergy also takes the Second Law of Thermodynamics into account; energy that can do work is distinguished from energy that is lost as heat to the environment. The calculations based on eco-exergy consider the total loss of work energy in the environment including the work energy associated with the information embodied in the genomes of organisms. The diet based on fishery-derived ingredients was the highest total work energy consumer compared with plant-based diets (24–30% greater), the diet containing krill meal (25% greater), and the algae diet (four times higher). Thus, reducing FM and fish oil levels in fish feed can contribute significantly to more sustainable aquaculture. In particular, algae-derived products in aquafeeds could drastically decrease environmental costs in the future.

1. Introduction

As the aquaculture industry continues to expand globally, access to key feedstuffs, such as fish meal (FM) and fish oil, will become increasingly limited because of the finite resources available for wild harvesting (Gatlin et al., 2007). Aquaculture that relies on FM as a dominant protein ingredient is another source of pressure on populations of wild fish (Pauly et al., 2002). To reduce the effect of aquaculture on the ecosystem, enhanced efforts are needed to thoroughly evaluate reasonable alternatives, such as feedstuffs from plant origin (Gatlin et al., 2007). Wheat gluten and soy protein concentrate (SPC) have shown high potential as alternative proteins to FM with respect to their availability and nutritional value. However, it is not straightforward to conclude that plant proteins inherently contribute to sustainability if we take into account the renewable and nonrenewable resources and waste emissions related to the production of these feed ingredients. The theoretical impact of replacing FM and fish oil in rainbow trout feeds was investigated using nutritional modeling and life cycle assessment by Papatryphon et al. (2004). They showed that completely replacing FM and fish oil with plant sources did not decrease the

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environmental impact when use of energy is considered. In addition, it was previously reported (Draganovic et al., 2011) that replacing FM with gluten, and particularly SPC, increases the quantity of water added during fish feed production to compensate for differences in the technological properties of fish and plant protein. Consequently, energy consumption for drying has to be increased. It can be concluded that there is a need for a comprehensive analysis of different protein sources in fish feeds.

We proposed using three thermodynamic analyses to provide an ecological evaluation of the differences in sustainability of various salmon feed compositions.

(A) Energy analysis has been applied traditionally to compare the energy consumption per kilogram of production of different salmon feeds. In this study, not only the energy of processing of feed ingredients is considered but also the direct energy inputs related to agricultural production and the processing systems from which the feed ingredients were derived (Pelletier and Tyedmers, 2007).
(B) Energy can, however, be energy that can do work or energy that cannot do work but is lost to the environment as heat by the temperature of the environment. Energy is conserved (the First Law of Thermodynamics), whereas energy that can do work (often named exergy) is lost inevitably by all processes (the Second Law of Thermodynamics). Humans are interested in the work energy, not in the heat energy lost to the environment. It would therefore be beneficial to compare different salmon feeds by the amount of exergy that is consumed in their production. The exergy content of the feed itself would be equal to the free energy (chemical work energy) of the various components. But the work energy related to production, such as electricity and fossil fuel, has to be included as well (Balkan et al., 2005; Dewulf and Van Langenhove, 2002; Kotas, 1986; Tekin and Bayramoğlu, 1998). Szargut (1989) described a method to calculate the exergy for a given chemical composition. Exergy is defined as the amount of work the system under consideration can perform when brought into equilibrium with the environment (room temperature and 1 atm). Exergy is therefore calculated slightly differently than the free energy because exergy has the environment as a reference.
(C) Classical exergy analysis does not consider that living organisms carry a lot of information. Information is a form of free energy according to Boltzmann (1905), which implies that living organisms contain more work energy than just the chemical energy of their components (proteins, lipids, carbohydrates, etc.) (often named eco-exergy). The information in organisms is embodied in the genome and is used to determine the amino acid sequence in the enzymes that are controlling the biochemical processes in living organism.

By calculating eco-exergy and including other exergy degradation, the total embodied work energy capacity can be calculated; this is the chemical work energy (free energy) of the chemical components, the work energy used for production, and the work energy embodied in the information that the living organisms carry. It means that the salmon feed with the lowest total work energy capacity or degradation is the preferred salmon feed from an ecological or sustainability point of view.

The primary aim of this paper is to estimate the impact of alternative ingredients to fish meal and fish oil on the environment, regardless of the geographic region of fish feed production. As a secondary aim, we want to introduce eco-exergy as a key driver for sustainability of aquaculture.

The diets considered in this work were formulated to be nutritionally equivalent or biochemically optimal to ensure maximum growth of salmon. Therefore, identical growth performance could be expected in fish fed different diets for this study.

2. Materials and methods

2.1. Methods

Fig. 1 shows the system chosen for the analysis. The system boundaries include the agriculture of wheat, grain legumes, oil

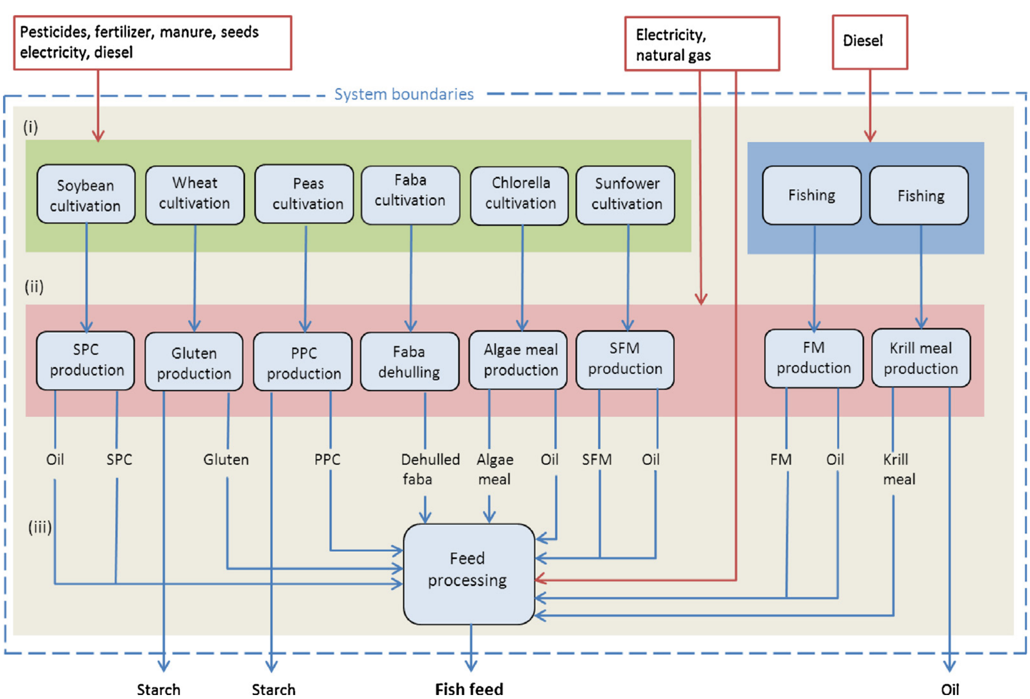

Fig. 1. System boundaries for the production of fish feed representing: (i) primary production/fishing, (ii) industrial stage ingredient preparation, and (iii) industrial stage mixing of ingredients and processing. The streams of all ingredients included in this study are shown. SPC, soy protein concentrate; PPC, pea protein concentrate; SFM, sunflower meal; FM, fish meal.