Circular Economy for Fish Farms in Araucanía, Chile

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Abstract. In its freshwater phase, salmon farming generates environmental liabilities such as fish faeces, unconsumed food and the natural mortalities of the productive process. The latter are treated with formic acid and used integrally in the manufacture of flours for animal feed. In turn, it is estimated that approximately 10% of the food supplied to the fish is not consumed and that the remaining 90%, after being digested, produces 13% of faeces. Both residues go through a stabilising pre-treatment and concentration process and are then removed as sludge. At present, the sludge is mainly disposed of in sanitary landfills, where their stench affects local communities. Moreover, CO₂ is released into the atmosphere due to sludge decomposition, contributing to the net carbon footprint of this industry and adding to the global problem of greenhouse gas emissions. In Chile, there are 957 freshwater fish farms, which generate 522,182 tons of sludge per year as a waste product. The management of this waste gives rise to considerable environmental, economic and social concern. Such a problem is mainly located in the Araucanía Region (Chile), where 53 industrial fish farms are located and two out of five of the salmon that Chile exports are born. In the context of the Circular Economy, our research group has been working on three research projects, aimed at adding value to the sludge. These are: 1. Use of sludge as raw material for obtaining heat energy, 2. Use of sludge as an amendment to agricultural and forest soils, and 3. Use of liquid waste from the sludge pressing process for fertigation. When using sludge as a source of renewable energy, previous studies corroborate that the calorific value of the obtained pellet ranges between 4,612 and 4,886 kcal/kg. Thus, such pellets have the potential to be used in the productive process of salmon farms, increasing their sustainability. A project has been developed to investigate and prototype a product we will call “soil amendment”, using a mixture of the sludge from fish farms and the resulting brush from the processing of algae. Finally, in order to reduce the sludge nitrogen and phosphorus concentration in clarification plants, the use of aquaponics and hydroponic techniques are studied. The flower known as chrysanthemum (Chrysanthemum spp.) was selected as a model species because of its commercial value and ease of handling. In the present work, the results associated with these three local cases of Circular Economy in Chilean freshwater fish farms will be presented.
1. Introduction
The productive activity of fish farms mainly generates solid (ISW) and liquid (ILW) wastes. The ISW, called “sludge”, corresponds to fish faeces and residual unconsumed food. ILW consists of fish urine and other dissolved physiological metabolic compounds. Both ISW and ILW are removed using combined separation methods, for instance, decantation-filtration-dilution. In the case of ISW, a sludge cake containing between 75 to 85% (w/w) of water is obtained as the final product, whereas the ILW is dissolved in the effluent water of fish farms. The regulations indicate that the maximum limits of liquid waste that may be discharged into water bodies from rivers are 50 mg/L total nitrogen and 10 mg/L total phosphorus.

Climate change is one of the biggest challenges that humanity has to face today. The massive generation of waste, such as sludge in fisheries wastewater treatment plants and algae wastes, causes strong environmental impact. Therefore, the management of this waste always gives rise to considerable environmental, economic and social concern, mainly at the regional level in Araucanía. This is associated with the management and final disposal of residues, due to the high volume of sludge that is generated. In Chile, there is a regulation for the management of sludge generated in wastewater treatment plants, which does not allow its direct disposal. In most cases, sludge is stabilised, dehydrated and disposed of in landfills (64% of the national total), without any alternative use that could generate value. So far, the main proposals for the use of such waste have been focused on the generation of biogas (methane) (Goddek et al., 2018). However, high investment is required to install this kind of plant, and thus it is necessary to find other cheaper alternatives for the mass use of residues that could also add value.

The sludge in the form of Industrial Solid Waste (ISW) generated in fish farms has a high environmental impact, both locally and globally, and especially affects the bottom of water bodies. This is one of the great environmental concerns of the country and is especially relevant in salmon farming. In addition, sludge may contain pathogenic microorganisms, parasites and chemical residues such as spawning inducers, anesthetics, antimicrobials and disinfectants (Hepp, 2012).

2. Case 1. Sludge for combustible biomass
In one of our team projects, the sludge from fish farms is used to obtain pellets for use as a source of energy. In this way, organic waste could be converted into a renewable energy source (Figure 1). It has currently been established that after the sludge is subjected to mechanical treatment for removing water excess, thermal drying treatment is necessary. This process expedites the handling of solid sludge, e.g. transport, storage, and disposal (Li et al., 2016). It was determined that pellets from fish sludge have a lower calorific value of 4,612 kcal/kg and a higher calorific value of 4,886 kcal/kg.

![Figure 1. Press filter and sludge accumulation ponds in a fisheries facility.](image)
being digested produces 13% of faeces. Therefore, the amount of dried mud would theoretically correspond to 23% of the total food delivered daily to farmed fish.

Taking into account that by 2015 the production of salmonids was 834,168 tons, using a biological conversion factor of 1.3, the amount of food used was 1,084,418 tons. Considering that only 5% food is occupied in freshwater fish farms, it is estimated that 34.17 tons of sludge are generated daily during freshwater production. This sludge needs to be deposited in authorized landfills, which involves extra expense for the companies. In addition, they constitute a worrying environmental liability. So, the use of fish sludge as a source of energy seems to be a viable alternative.

3. Case 2. Use of seaweed as soil amendments and for silage production

The Chilean Ministry of Agriculture maintains a “Degraded Soil Recovery Program” with a strong emphasis on phosphate fertilisation, limestone amendments, meadows, soil conservation practices, and crop rotation. However, it does not stimulate the use of residual sludge (Hepp, 2012).

Nonetheless, the seaweed industry has grown dramatically in recent years. In 2012, aquaculture produced more than 23 million tons of dried seaweed, mainly for human consumption (Loureiro et al., 2015).

Seaweed marine processing wastes and those produced by algae strands are disposed of in municipal landfills without any previous treatment. In both cases, transport and disposal of these wastes involve costs for the companies that generate them. Therefore, if the idea is to turn Chile into a country based on a “Circular Economy”, extending the lifetime of products, it is necessary to reuse these wastes and convert them into inputs for the generation of new value-added products.

At the Universidad Católica de Temuco, three preliminary trials have been carried out using seaweed residues called “brush” (particle size 0.5 to 1 cm), and seaweed strands as a soil amendment (dose study). Different types of both organic and inorganic fertilizers were evaluated: Aerobic dry seaweed silage with composting of plant residues (T1), earthworm humus (T3), aerobic algae silage (T4), anaerobic algae silage (T5), superphosphate fertilizer (T2), with the use of vegetable soil with no fertilizer added as the control treatment (Jara, 2019).

The fertilizers were tested for 70 days in experimental oatmeal crops. The results showed that the T1 treatment produced greater plant growth and development stimulation. This treatment showed the best results in the measured parameters: plant length (cm), plant weight (g) and leaf length (cm), 35 days after plant germination.

Recent studies have examined the potential of silage methodology to preserve algae by means of aerobic and anaerobic digestion (Mardones and Cordero, 2012). As a result, a stable material is produced that contains moisture and is preserved in an acidic medium. Traditionally, this has provided feed for livestock when fresh fodder is limited or unavailable. Similarly, silage could be a non-seasonal supply of material for bio-renewable applications in agriculture.

In recent years, various research projects on seaweed silage for different applications (animal feed, biofuels, etc.) have gained strength (Cabrita et al., 2017; Herrmann et al., 2015). In Chile, a FONDEF D05110224 project was carried out at the Universidad Católica de Temuco, where abalone feed was developed from silage algae. It was shown that through silage the seaweed nutrients became bioavailable to the abalone, improving their assimilation (Mardones et al., 2015). Therefore, there is certain evidence to support the use of seaweed silage process and the advantages that the final product offers.

4. Case 3. Use of sludge for fertigation

A study was carried out by the Universidad Católica de Temuco in conjunction with a fish farm in the Araucania Region, for the reduction of nitrogen and phosphorus in the ILW generated by the plant treatment. The potential for use of this ILW in fertigation in plant nutrition was examined. The use of adapted aquaponics and hydroponic techniques to reduce the macronutrient load (N and P) was evaluated (Figure 2) because they are similar to the fertigation levels applied to hydroponic crops (Monsees et al., 2017).
Among the main cultivation technologies are: Floating root system (FRS), where the roots of the plants remain in contact with water that must be oxygenated daily. The FR system is the most widely used hydroponic cultivation system on a commercial scale. A pond is needed to store the nutrient solution, an automated pumping system and an interconnected tube system. Holes are made to place the plant containers. In the solid substrate system, a solid medium (substrate) is used to support the roots of plants and is the most commonly used in popular hydroponics and aquaponics (Colagrosso, 2014).

Considering the existing alternatives, the implementation of a gutter method was proposed, consisting of the constant circulation of a layer of nutrient solution and water. In this case, the ILW passes through the roots of the vegetable crop, thus avoiding losing or spoiling the nutrient solution. Therefore, it is transformed into a closed ILW storage system where the ILW is recirculated through the system via PVC pipes and a pump. In addition, a storage tank with tap water without nutrient can be maintained. Thus, the ILW is available for application in plants and also makes it possible to prepare the desired mixture of water plus ILW nutrients. In this way, the dose of nutrients can be adjusted according to plant mineral requirements. The N and P concentrations to be used are corrected on the basis of periodical plant foliar analysis.

Absent macro and micronutrients in the ILW should be added externally. It was determined that nearly 900m² of chrysanthemum plant culture with a plant density of 20 plants per m² would be needed. This way, 96% of the volume produced per day was treated, according to calculations based on ILW nutrient concentration.

According to Calvache (2013), the optimal type of plant for use in nutrient extraction is the chrysanthemum (*Chrysanthemum morifolium*). This is due to the high frequency of application of fertigation compared to other cut flowers and the increased nutrient requirement. In addition, in the Araucanía Region, there are successful chrysanthemum plantations, which would indicate that a cold climate is not an impediment to their cultivation (Chahin, 2000).

Regarding concentrations of P in the ILW, from March 2014 to July 2015, an average of 11 ± 5 mg/L was used considering a chrysanthemum water requirement with a dose of 25 mg/L fertigation. It is useful to note that the P concentration in the ILW is 14.2 mg/L below the required concentration for plants. In the case of N concentrations, there was an average concentration of 49 ± 19 mg/L, which is in the same range as the 50 mg/L that this plant requires for optimal growth. Given the frequent application of ILW with a sub-optimum concentration of nutrients and the fact that chrysanthemums do not suffer from phytotoxicity, it is estimated that nutrients absorbed by plants can be reduced.

With regard to the N and P concentrations in the ILW flow from the fish farm, 900 m² of chrysanthemum flower cultivation at a density of 20 plants/m² are required if the aim is to reduce the N and P concentration from ILW by 96%.
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