

DOI: 10.18462/iir. 10.18462/iir.icr.2023.0542

Sustainable production of fish protein hydrolysates: overall system architecture and footprint

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ABSTRACT

In this research work, the most efficient and energy-saving techniques for fish protein hydrolysates production were investigated from cradle-to-gate, in terms of overall cooling, heating, and energy demands. Advanced techniques for concentrating and drying the FPH was examined in detail to identify the process combinations with efficient energy use. The direct drying process consumes significant energy between 1.53 to 1.8 kWh kg⁻¹ of water removal. Concentrating using freeze concentration, three stage evaporator and mechanical vapor recompression (MVR) before the drying process resulted a reduction in the overall energy and the CO₂ emissions levels are calculated lower. The energy recovery solutions were investigated with integrated heat recovery using a transcritical two-stage CO₂ system in Dymola & EES. The simulation results have the heat pump COP of 3.5. Integration of heat pumps with the spray dryer resulted significant energy reduction of up to 71.5 %. Finally, the economic assessment has been carried out.

Keywords: Fish protein hydrolysates (FPH), Industrial drying techniques, vacuum freeze concentrator, vacuum drying, Heat pump drying, Energy savings.

1. INTRODUCTION

Fish protein hydrolysates (FPH) can be used for different applications as a feed food for animals, aquatic fish, to high-quality protein mix for humans. Protein from fish can be used to produce bioactive peptides and FPH, which increases the economic value and decreases the environmental impacts (Himaya et al., 2012). The liquid state of FPH has a high amount of water content, which is relatively unstable, and reduces shelf life, hence long-term storage and transport was limited. The removal of moisture from FPH is difficult and involves high costs. Drying can be performed either using spray dryers, vacuum freeze dryers or drum dryers which removes the moisture content and lowers the value to 1-3% (Petrova et al., 2018). Spray dryers which are widely used in industries, consumes the energy around 4500 and 11500 kJ kg⁻¹ of water removed (1.25-3.2 kWh kg⁻¹). The process design modification can lead to reducing energy use (Mujumdar, 2007). Other pilot models proposed by Al-Mansour et al. (2011), have a minimum specific energy demands of around 5500 kJ kg⁻¹ (1.53 kWh kg⁻¹). Freeze drying and rotary drum drying also consume high amount of energy. Hence drying process generally is highly energy intensive.

The concentrating methods are used as a pre-step before drying methods. This combination results in greater energy savings. Schuck et al. (2015), studied the energy demands by combining the vacuum evaporation and spray drying methods during production of dairy powders and established calculation equations which compute the lowest energy charges for dairy powders. They found that to produce the dairy powders, the energy costs are at 1.7 kWh kg⁻¹ (6120 kJ kg⁻¹). Freeze concentration can be performed before the drying stages, to lower the overall energy demands. The freeze concentration procedure is a gentle way for dewatering food products with a concentration of 30%. Studies investigated by Miyawaki et al. (2005), stated

in his research work, that the freeze concentrators consume the energy of around $\sim 330 \text{ kJ kg}^{-1}$ of water to freeze.

Other alternative methods used in concentration process, are evaporation techniques, membrane filtration methods. For evaporating 1 kg of water the energy value required is approximately $2,700 \text{ kJ kg}^{-1}$ (0.75 kWh/kg). With improvement in methods, multistage evaporation (MSE) method, Mechanical vapour recompression (MVR) method can be used, the energy reduction can be achieved. Han et al. (2021), experimentally investigated the MVR system and concluded that with two effect evaporator 40% more energy saving was achieved than a single-stage MVR system.

From the above literature review, it is identified that research findings related to energy-efficient techniques in the production of fish protein hydrolysates, and its optimization are limited and are available in scanty. Also, there is no well-established economic analysis of technologies associated with FPH production. Hence, in this study, the main objective is to identify the energy use in each process, identify the process with high energy use and suggest the energy reduction measures in a sustainable way.

The main motivation for working in this research area is because the thesis addresses major societal problems and provides effective solutions. The thesis investigates sustainability issues and connects people, profit, and the environment by identifying energy-efficient processes for energy reduction, establishing ways for reducing global emissions, and indicating how profitable the various process alternatives are.

2. METHODS

2.1. Description of hydrolysis process

The fish RRM is diluted with water and insignificant amount of enzymes (0.1% approx.). The protein molecules are broken into the smaller structure of peptides and amino acids with the help of enzyme during hydrolysis. During the hydrolysis process, the solution is heated to hydrolysis temperature of $50 - 55 \text{ }^\circ\text{C}$ and the enzymes were added to the RRM mixture. Heating the mixture to the hydrolysis temperature demands a higher amount of energy. Generally, the hydrolysis process can take up to $60-120 \text{ min.}$ and in some cases even longer time. The temperature and process parameters are well controlled during the entire process and the mixture is uniformly stirred during the entire process to have a uniform temperature distribution.

After the completion of the hydrolysis process, the solution is pasteurized to a high temperature of $90 \text{ }^\circ\text{C}$ and the mixture is stirred for another $15-20 \text{ min.}$ This process is carried out to reduce the microbial activity and to inactive the enzymes present in the solution. Various types of tricanors and polishers are used to separates solid sedimentation form the liquid hydrolysate. The typical example of the process is shown on Figure 1.

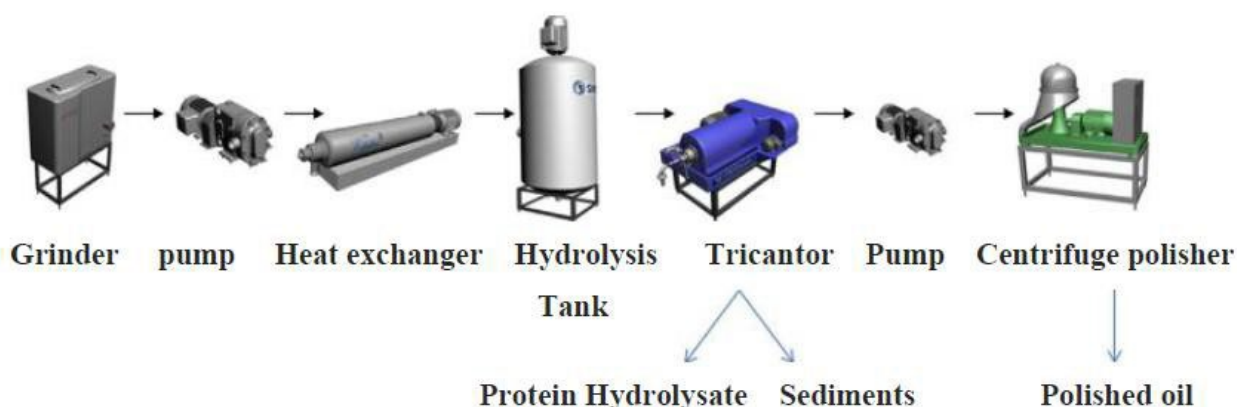


Figure 1: General process flow diagram in production of fish protein hydrolysates (Slizyte et al., 2014)

2.2. Process-flow diagram

The study was performed for 1000 Kg h⁻¹ of rest raw material (RRM) – Atlantic Cod heads and 1000 kg h⁻¹ of water. Two types of RRM (chilled and frozen) were used in the production of hydrolysates. RRM had 77.7 % of water, 14.6 % of proteins, 0.4% of lipids and 7.3 % of ash. In the calculation, it was considered to have approximately 7% solids with 6.6% protein content and 0.2 % of ash in the FPH after separation (tricanter). The protein unsolved mixture has 80% protein and 20% water.

The general process flow diagram of the production of fish protein hydrolysates with different concentration and drying alternatives is given in Figure 2. The concentrating methods were compared in combination with drying methods. The energy study involves a detailed investigation of freeze concentration, evaporation in the concentrating process and drying using spray drying method, vacuum freeze drying, rotary drum drying, heat pump assisted drying.

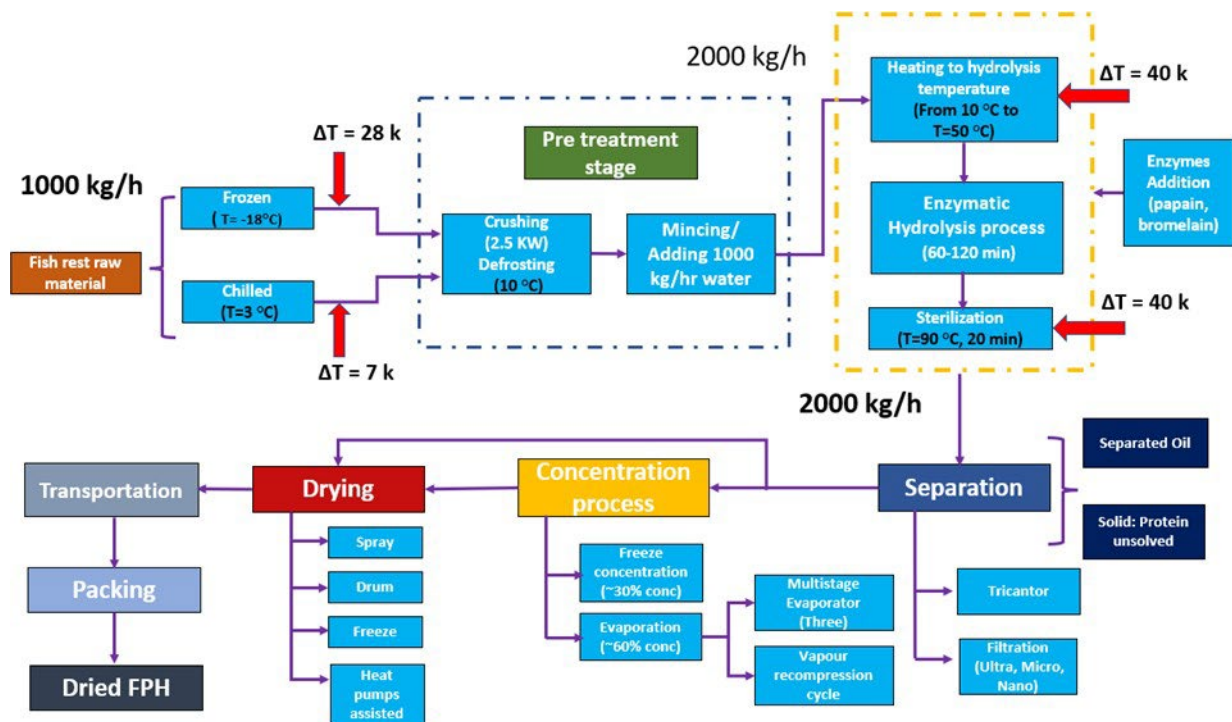


Figure 2: General process flow diagram in production of fish protein hydrolysates

Freeze concentration is a technique that involves freezing and removal of water by fractional crystallization of water into ice. The hydrolysates were initially cooled to +4 °C from 90 °C in the freeze concentration process. In the process, the inlet mass flow rate was 1841 kg/hr, the hydrolysates are concentrated at 30 % solids from the initial feed temperature of +4 °C to the final freezing temperature of -3° C. The refrigeration system operates at two levels 0 °C and - 40 °C.

In the evaporation process, the final solid content in concentrate was considered to be 50% for calculation. The mass flow rate of hydrolysates in the evaporator was at 1841kg/hr. In three stage evaporator the vapour from the previous stage was used as a heating medium in the next stage which reduces the energy demand.

In mechanical vapour recompression system, the vapour from the feed solution is heated using a compressor or a blower fan which increases the pressure and the temperature sufficiently for energy transfer. The energy possessed by the vapour is reutilized for heating the feed. The cycle operates at pressure of 1.5 bar. A re-heater can also be used at the exit of the compressor based on the temperature requirements.

In spray drying, the heat input required to evaporate the water included (i) the heat required for heating the water vapour and evaporating the water, (ii) heat required for heating the solids in the feed, (iii) the amount of heat required to heat the remaining water in the product.

In rotary drum drying, the air temperature is usually 300 °C and the hydrolysates are dried to ~98% solids. The required heat is provided by the exchange of heat between the hot air and the product. The following assumptions to be considered, (i) Heat to raise the temperature of the feedstock solid. (ii) Heat lost in residual moisture; (iii) heat carried away by the amount of moisture present in the exit feed. (iv) The heat required to raise water temperature to saturated temperature. (v) The heat required to raise the temperature of the water to vapour temperature, is given by the product of the mass of vapour to the latent energy, (vi) heat loss and additional energy required for heating the air.

In vacuum freeze-drying, the sublimation of the product occurs at -20 °C inside the freezing chamber at pressure ~1.0 mbar. The product is frozen from initial feed temperature to temperature of -20 °C. After this sublimation of ice occurs, which results in the direct phase change of ice into vapour without liquid phase. The heat energy required during the process will be the difference in enthalpy between the saturated solid state to the saturated gas state of water at -20 °C and 1 mbar. The freezing load is provided by the refrigeration capacity to transform water vapour to ice on the evaporating surface. It is given by the difference in enthalpy of saturated gas at -20 °C to the solid at -40 °C at the same pressure. Other additional energy was considered in the vacuum freeze-drying is the work input to the compressor to provide the necessary cooling capacity at sufficient temperature. The Carnot COP of the refrigeration capacity is calculated at $T_h = 30$ °C and $T_l = -50$ °C. The work input of the vacuum pump to maintain relatively low pressure during the entire drying process was also calculated.

2.3. Energy recovery solutions

The two-stage system using CO₂ was studied for energy recovery for cooling, heating and freeze-concentration processes. The production of FPH requires intensive heating and cooling at various stages. The conventional heating techniques require higher energy demands. Heat pumps are energy-efficient solutions, the investigation of the heat pump was simulated to study the process of heating and cooling requirements. In the design, first, it was considered to simulate the heating of the hydrolysates and water mixture to the hydrolysis temperature of 50 - 55 °C at the main heat exchanger (gas cooler). Next, the refrigerant is subcooled in the sub-cooler, the released heat energy is used to melt the 15% of ice for the case, when freeze-concentration method was applied. The system model is given Figure 3.

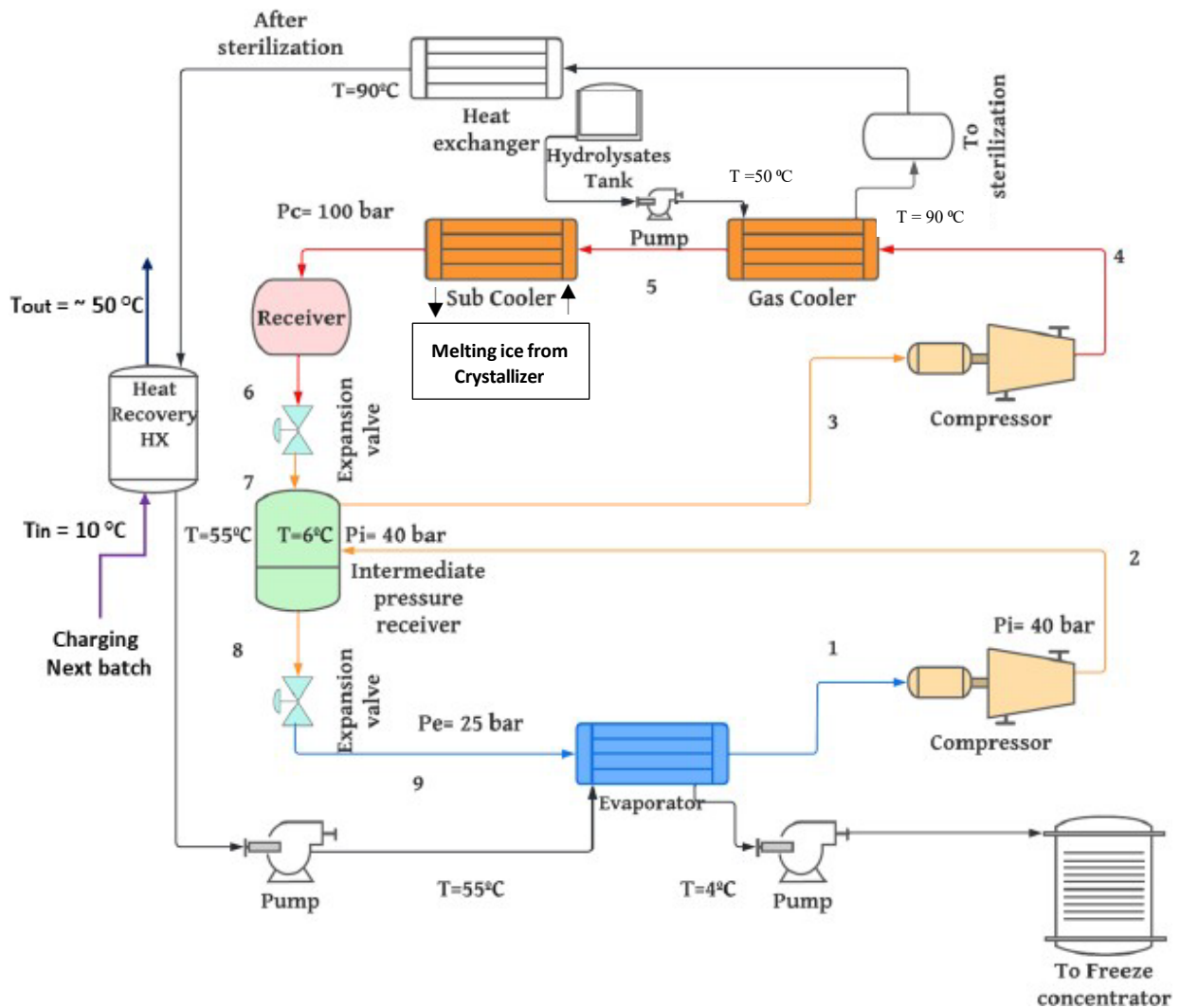


Figure 3: Two-stage CO₂ heat pump simulation model.

During the freeze concentration process, the hydrolysates mixture was cooled to +4 °C since the temperature after sterilization was higher at 90 °C. This heat can be made recovered to heat the incoming hydrolysates water mixture from 10 °C to around 50 °C. Charging of fresh hydrolysates mixture is performed to recover the waste heat in the heat recovery heat exchanger. The heat source for the process is taken from the waste heat, which is exchanged with heat recovery HX, the outflow FPH has a temperature of around 55 °C. This is cooled to 4 °C by the evaporator. The heating of hydrolysates and energy recovery are simulated using Dymola software to study the system behaviour in a dynamic environment.

Heat pump assisted drying can provide greater energy savings for the drying process. The heat rejected from the heat pump system is used to heat air to high temperatures up to 150 °C. In our study high temperature heat pumps were considered. The following propane-butane system design (Figure 4) has been studied in EES software to study the system behaviour and application of HTHP in the production process of fish protein hydrolysates. Butane working fluid at the top stage is best suited for high-temperature heat delivery due to its higher critical temperature, up to 120 °C.

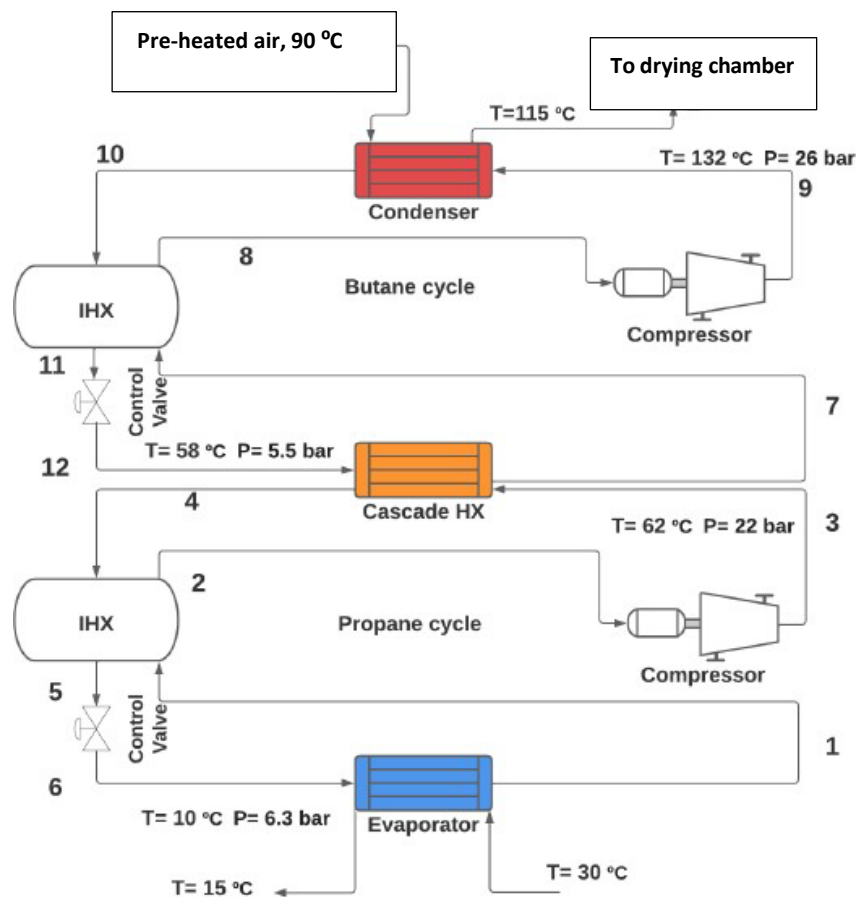


Figure 4: HTHP system: Propane-Butane cycle

2.4. Calculation tools

Engineering Equation Solver (EES) is a program which is used to solve nonlinear systems of equations. The trans-critical CO₂ system and the HTHP model has been designed and analysed in the EES. EES has a comprehensive database of the properties of several refrigerants used in refrigeration systems.

Dymola is a modelling and simulation program that uses the open Modelica modelling language. It is capable of handling quite complicated systems and is utilized in aerospace, automotive, robotics, process, and other industries. For dynamic simulations, TLK-Thermo GmbH's Dymola software was used, along with TLKThermo GmbH's components and refrigerant libraries. TIL 3.5.0 libraries were utilized to simulate heat exchangers, compressors, and valves, as well as TIL Media 3.5.0 for refrigerants and secondary fluids. The transcritical CO₂ system has been simulated in Dymola and the results were compared with EES.

2.5. Economic analysis

The economic analysis was performed based on the approach for process engineering economics, (Couper, 2007; Hillestad, 2022). The profitability analysis was performed in accordance with investment analysis (Georges, 2020). The equipment cost was taken from reliable product manufacturing sites based on the production capacity. Important equipment costs in concentration and drying stages are validated with relevant literatures who had performed study on economic analysis.

2.6. Carbon footprint

The life cycle study includes all the foreground and background processes that are the contributors to environmental impacts. For any production, there are both direct and indirect emissions associated with the process. The life cycle assessment calculates the complete impacts and emissions generated from the

process. In Norway, since the electricity generation is from hydropower it results in less emission of $\sim 6 \text{ g CO}_2 \text{ eq/kWh}$. However, for the same electricity production, if its source is varied, the corresponding emissions will change. Hydropower based electricity production has the lowest emissions while coal-based electricity production has higher emissions.

3. RESULTS AND DISCUSSION

3.1. Overall energy consumption

It was identified that the major consumption of energy occurs in the drying stage. At the drying stage, when analysing the alternative process with freeze drying, spray drying and drum drying, all dryers consume a significant amount of energy between 1.5 to 1.88 kWh kg⁻¹ of water removed.

The total energy requirement when concentrating 1000 kg h⁻¹ of rest raw material to 131.5 kg h⁻¹ (98% solids) is given below in Figure 5. It is observed from the table, that the direct drying of FPH consumes significant amount of energy use. Hence, concentrating techniques before the final drying process should be implemented to reduce the energy demands. When concentrating 30% solids of FPH by freeze concentration and then final concentrating with drying methods, results in lower energy consumption around 1120-1245 kWh for 1 ton of rest raw material. Which is 60 % energy savings when compared with direct drying methods.

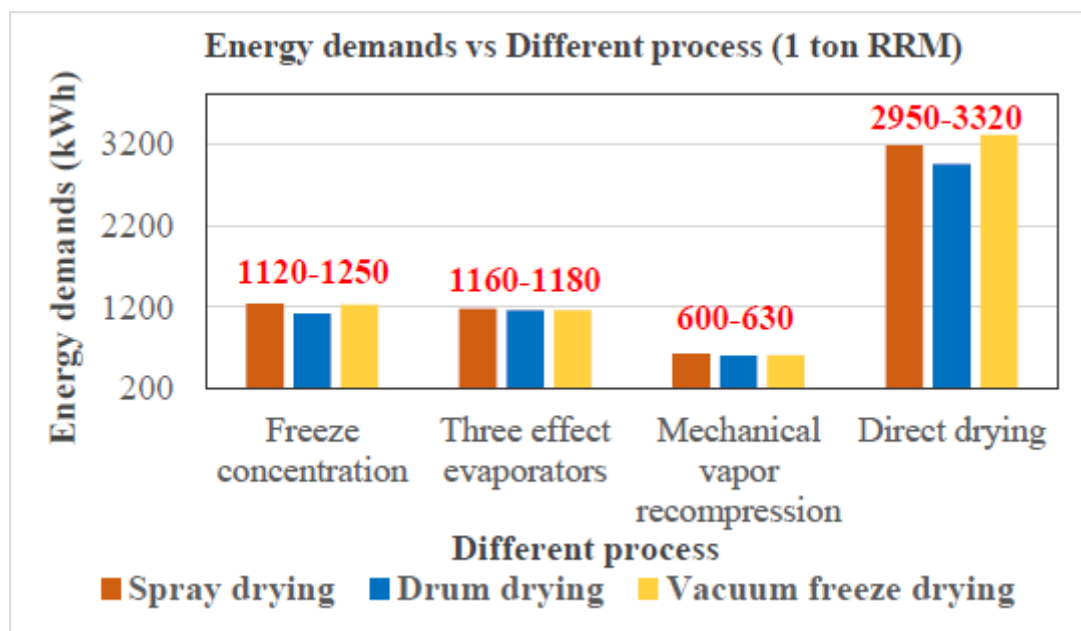


Figure 5: Energy demands vs Different processes for 1-ton RRM

Energy use in the concentration process like freeze concentration, MSE, and mechanical vapour recompression results in lower energy demands. Freeze concentration consumes energy of 273 kJ kg⁻¹ of water to freeze and the mechanical vapour recompression evaporator (MVR) has the lowest energy demands value of around $\sim 150 \text{ kJ kg}^{-1}$ of water when compared with other processes and provides significant energy savings. The three-stage evaporator is also one of the most energy-efficient ways of evaporating the water from the feed solution. Since the energy or heat possessed in the vapour is reutilized to heat the inlet feed, in this way the energy supplied to the system is reduced significantly. In mechanical vapour recompression, a large amount of heat is transferred with little work and hence energy is recovered in the process.

3.2. Energy recovery and use of high temperature heat pumps

The two-stage CO₂ trans-critical heat pump was simulated to evaluate the possible energy recovery from the hydrolysis process: heating and cooling of hydrolysates at different temperature levels. The design is made in such a way as to reduce the charge by lowering the condensation pressure. The work input to both

the compressors was calculated to be 45 kW, and the total heating capacity was calculated as at 148.8 kW, COP of the heat pump was 3.3. The highest energy recovery was calculated for combination of trans-critical heat pump with the freeze-concentration systems, when the low temperature gas-cooler is used for ice melting. The overall energy savings for heating were accounted in the range between 70 and 85 % with respect to the type of concentration system used.

The high temperature heat pump butane condensing pressure was at 23 bar when COP of 2.1 was achieved. This cycle was operated at higher condensing pressure to provide a higher temperature output and hence the COP of 2.1 was obtained. The corresponding network input to the cycle was 171 kW, while the total energy required for the spray drying of 1 ton RRM per hour was 500 kWh (in the case of application of freeze-concentration). Thus, the propane-butane high temperature heat pump can compensate the 71.8 % of all the energy required for spray drying of freeze-concentrated product.

3.3. Economic analysis

The summary of the economic analysis is shown in Table 1. The analysis is given based on 5000 hours per year production (130 kg of dried powder per hour). The use of freeze-concentrators has a longer pay-back time and higher investment costs. This is explained by the fact that the final concentration of the FPH after the freeze-concentration process is 30 %, while the other two methods can provide up to 50 % dry matter in concentrate. However, this difference does not reflect the quality of the hydrolysate produced by freeze-concentration, which is suspected to be higher due to low temperature and gentle treatment.

Table 1: Economic analysis results

	Freeze concentration	Three effect evaporators	Mechanical vapour recompression	Direct drying
Investment costs, mln. USD				
Spray drying	8,4	7,7	7,4	6,3
Drum drying	8,2	7,5	7,2	6,1
Vacuum freeze drying	8,9	8,2	8	6,9
Payback time, years				
Spray drying	5,3	3,7	2,2	-
Drum drying	5,7	4,2	2,4	-
Vacuum freeze drying	4,8	3,4	2	-
Depreciation cost per year, mln USD				
Spray drying	0,42	3,6	3,5	0,32
Drum drying	0,41	3,5	3,4	0,31
Vacuum freeze drying	0,45	3,8	3,7	0,34

Beek et al., (2018), from GEA analysed a reference freeze concentration plant when concentrating 27% with membrane in pre-concentrating stage and further dried with spray drying, they observed a payback time of 4 years for a smaller plant capacity. Also, they mentioned the operational cost of a freeze concentration plant was greatly influenced by the size of the facility.

3.4. CO₂ emissions

Advanced technologies at the concentration and drying stages will benefit the process with greater energy savings in producing the fish protein hydrolysates. The energy savings will directly reduce the yearly CO₂ emission, this will greatly decrease the environmental impacts associated with these emissions. To

understand how potentially these technologies can offer the environment in reducing the CO₂ emission levels, the below study was performed with the different energy sources. Figure 6 represents the yearly CO₂ emission levels from the different processes when producing the FPH. The electricity generation was considered from hydropower-based type, for every kWh the direct and in-direct emissions account for a CO₂ emission of 6 g. It is important to note, that when the electricity is produced from coal-based source with carbon capture and storage technologies, the amount of CO₂ emission is produced at 240 g per kWh. For the hydropower source, it is seen that when spray drying at the drying stage produces a yearly emission of around 37 tons of CO₂ emission, and the process with a multistage evaporator (MSE) with spray dryer produces 35 ton of CO₂ emission. The same trend will be observed if the energy source will be coal or gas.

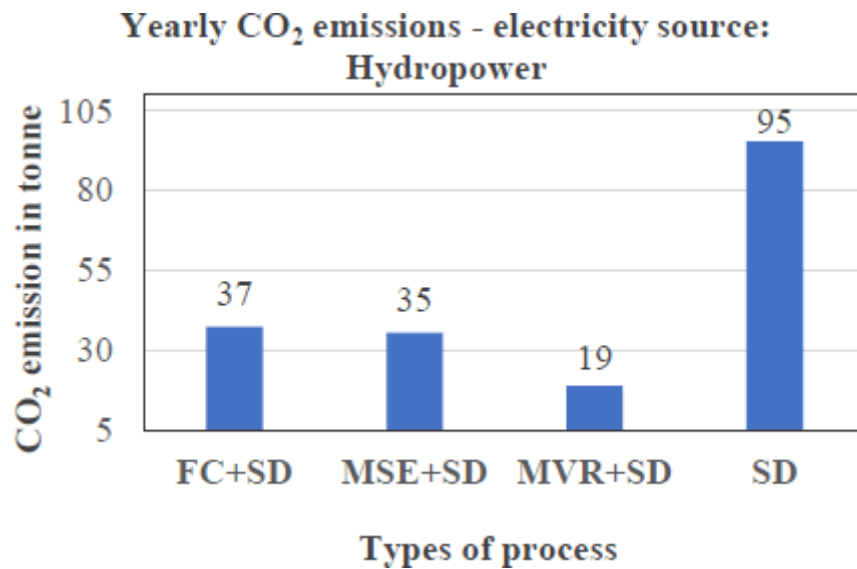


Figure 6: Yearly CO₂ emissions electricity source: Hydropower FC: Freeze Concentration, SD: spray dryer, MSE: Multistage evaporator, MVR: mechanical vapour recompression

4. CONCLUSIONS

Production of fish protein hydrolysates using conventional methods is generally an energy intensive process. In this thesis work, the energy demands in the production of fish protein hydrolysates were investigated in detail using advanced technologies to find the most efficient process. Concentrating and drying technologies are studied together to find an effective combination. The energy required with the process with freeze concentration process was in the range 1120-1250 kWh. The energy value for the process with three-stage evaporators was in the range 1160 - 1180 kWh and the process with mechanical vapour recompression was in the range 600-630 kWh. When compared with the direct drying process, greater energy savings was achieved. The final FPH powders were produced at the rate of 130 kg h⁻¹. Freeze concentration consumes energy of 273 kJ kg⁻¹ of water to freeze and the mechanical vapour recompression evaporator (MVR) had the lowest energy demands value of around ~150 kJ/kg of water when compared with other processes and provides significant energy savings. The three-stage evaporator is also one of the most energy-efficient ways of evaporating the water from the feed solution. Freeze concentration can be used as an effective process in combination with drying to produce the final FPH powder. The freeze concentration method decreases water content, increases shelf-life, stabilizes the quality of food, reduces further energy costs and is suited for heat sensitive products. Heat pump cycle assisted drying process with spray dryer has significant energy-saving

about 71.8%. The simulation results of the trans-critical two-stage CO₂ system in Dymola & EES resulted the heat pump COP of 3.5. It can be used as an energy recovery solution in the production process of FPH. HTHP can be used as an alternative for evaporation techniques to reduce the energy demand. The highest effect was achieved for combination with freeze-concentration method. Finally, the investment analysis resulted a payback time of 4.8 to 5.7 years for processes with freeze concentration and different dryers, 3.4 to 4.2 years

for processes with three-stage evaporators and dryers and 2 to 2.2 years for processes with MVR and dryer's combinations.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Research Council of Norway and industrial project partners for the financial support for carrying out the present research (NFR project No. 294662, CoolFish).

NOMENCLATURE

<i>FC</i>	Freeze-concentration	MVR	Mechanical vapour reocompression
<i>FPH</i>	Fish protein Hydrolysates	RRM	Rest raw materials
<i>MSE</i>	Multistage evaporator	SD	Spray dryer

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