Production of food products with a low content of lactose

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Abstract

The aim of the work is to design technologies suited for manufacturing plant-based coconut yoghurts and yoghurts made from hydrolyzed milk for an existing factory of milk products. Material and enthalpy balances are computed, economic evaluation of the projects including what-if analysis of selected parameter is carried out. Designed variants are compared.

Key words: lactose; lactose intolerance; veganism; membrane techniques; chromatography; yoghurt; balances

1. Introduction

Nowadays many people all around the world suffer from lactose intolerance – around 75 % of the world's population [1]. Lactose intolerance is a condition in which people have symptoms due to the decreased ability to digest lactose because most humans gradually lose the intestinal enzyme lactase after infancy [2]. At some point in prehistory, a genetic mutation occurred and lactase activity persisted in a majority of the adult population on Northern and Central Europe [1]. Lactose is a disaccharide. It is a sugar composed of galactose and glucose.

The global market is showing increasing demand in producing food items for people with special dietary restrictions. In recent times requirements and global demand for lactose-free and plant-based items have been rising as well, eventually for food items which do not contain casein (milk protein) or other substances which could be very harmful for some individuals.

Lactose-free yoghurts and plant-based alternatives of yoghurts are trending food items – especially for people who have special dietary restrictions such as lactose intolerance, for vegans and in generally for people who would like to have benefits from yoghurt which is packed with nutrients and is also very helpful for digestive system of human beings due to its impact on microbiota.

A number of available coconut yoghurts in stores does not increase. Another problem is that plant-based yoghurts and lactose-free yoghurts are usually distributed just to supermarkets and cities – they are not distributed to villages and towns.

1.1. Yoghurts made from hydrolyzed milk

1.1.1. Manufacturing process

Firstly, milk is standardized. Cream (in this case 40% cream is used) is added into skimmed milk due to the standardization. Skimmed milk contains 0.05 % fat. The resulting mixture is milk which contains 0.5 % fat. Standardized milk is homogenized and then pasteurization follows. Milk is pasteurized at 90 °C for 5 minutes due to the denaturation of whey proteins. Pasteurized milk is cooled to 15 °C in the first cooling section of the pasteurization unit, in the second cooling section milk is cooled to 4 °C. After cooling sections milk is thickened, the resulting content of dry matter is 15 %. Initial content of dry matter in milk is 10 %. Falling film evaporator is used. After all of these processes hydrolysis is done. The temperature of hydrolysis is 30 °C. After elimination of lactose milk is heated to 38 °C (inoculation temperature). After inoculation of the milk the mixture is heated to 42 °C (incubation temperature). The mixture incubates 10 hours while the constant temperature – the temperature of incubation – is maintained. After incubation the yoghurt is cooled to 5 °C. The yoghurt is filled into paper cups. The volume of a paper cup is 0,215 l.

1.1.2. Mass balance

All flows are shown in Figure 1. In Table 1 the mass balance is summarized.

The flow 1 contains skimmed milk (0.05 % fat), the flow 2 contains 40% cream. The resulting amount of milk – respectively standardized milk – is defined by the flow 3. The amount of standardized milk is equal to the amount of milk in the flows 4 and 5. The amount of evaporated water is represented by the flow 6. The flow 7 contains thickened milk. Enzyme lactase – respectively beta-galactosidase – is essential part of the hydrolysis. The flow 8 is equal to 0 due to a very little amount of this enzyme. Products of the reaction (hydrolysis) are glucose (flow 11) and galactose (flow 12). After hydrolysis fermentation is done. Starter culture is represented by the flow 13. The mass of this starter culture is very small so the flow 13 is set to 0, too. The amount of the starter culture is around tens of grams. In the flows 14, 15, 16, 17, 18 is the resulting product – yoghurt.

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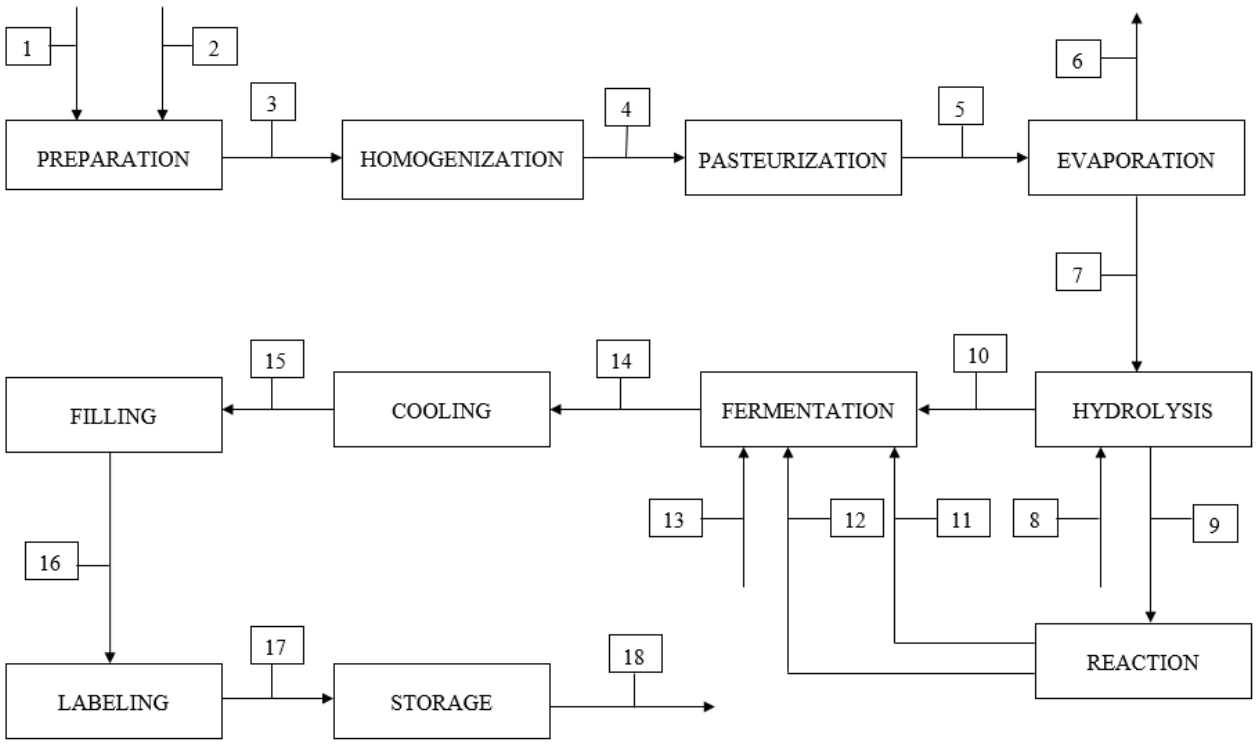

Figure 1. *Process scheme – mass balance.*

Table 1. *Yoghurts made from hydrolyzed milk - mass balance*.

Flow	Material	Mass	Unit
1	skimmed milk	154.26	kg/batch
2	40% cream	1.76	kg/batch
3	skimmed milk + cream	156.02	kg/batch
4	mixture after homogenization	156.02	kg/batch
5	mixture after pasteurization	156.02	kg/batch
6	evaporated water	52.01	kg/batch
7	thickened milk	104.01	kg/batch
8	lactase	0.00	kg/batch
9	reactants (lactase + water)	5.04	kg/batch
10	non-reacting part of the milk	98.98	kg/batch
11	glucose	2.52	kg/batch
12	galactose	2.52	kg/batch
13	starter culture	0.00	kg/batch
14	yoghurt	104.01	kg/batch
15	yoghurt after cooling	104.01	kg/batch
16	yoghurt - packaging	104.01	kg/batch
17	yoghurt - labeling	104.01	kg/batch
18	yoghurt - storeroom	104.01	kg/batch

1.1.3. Enthalpy balance

In the first regeneration section of the pasteurization unit milk is heated from 10 °C to 50 °C, pasteurized milk is used as a heat supply. This pasteurized milk is cooled from 65 °C to 25 °C at the same time. In the following regeneration section of the pasteurization unit milk is heated from 50 °C to 75 °C, the pasteurized milk is cooled again – from 90 °C to 65 °C. Milk is pasteurized at 90 °C for 5 minutes. Hot water is used for pasteurization. The temperature of hot water is 98 °C. Hot water is cooled to 90.5 °C during the process of pasteurization. Pasteurized milk goes through the first regeneration section and through the second regeneration section to the first cooling section. Cold water provides the cooling in the first cooling section. Cold water is heated during the cooling process from 8 °C to 10 °C. Ice water provides the cooling in the second cooling section. Ice water is heated during the cooling process from 1 °C to 8 °C. Milk is cooled from 25 °C to 15 °C as it goes through the first cooling section. Milk is cooled from 15 °C to 4 °C as it goes through the second cooling section.

Cooled milk is stored in a storage tank. The temperature of stored milk is 4 °C. In the falling film evaporator milk is heated to 70 °C. During the evaporation process the temperature of the milk raises up to 71.23 °C due to physicochemical depression.

All flows are shown in Figure 2. In Table 2 the enthalpy balance is summarized. All processes are considered to be isobaric. It means the change of the enthalpy is equal to the change of the heat. The minus sign before the value represents removed heat, the plus sing before the value represents supplied heat.

The heat required to heat the milk entering into the pasteurization unit is represented by the flow 1. The heat required to heat the milk which exits from the first regeneration section is represented by the flow 2. The flow 3 represents the heat which is essential for heating the milk

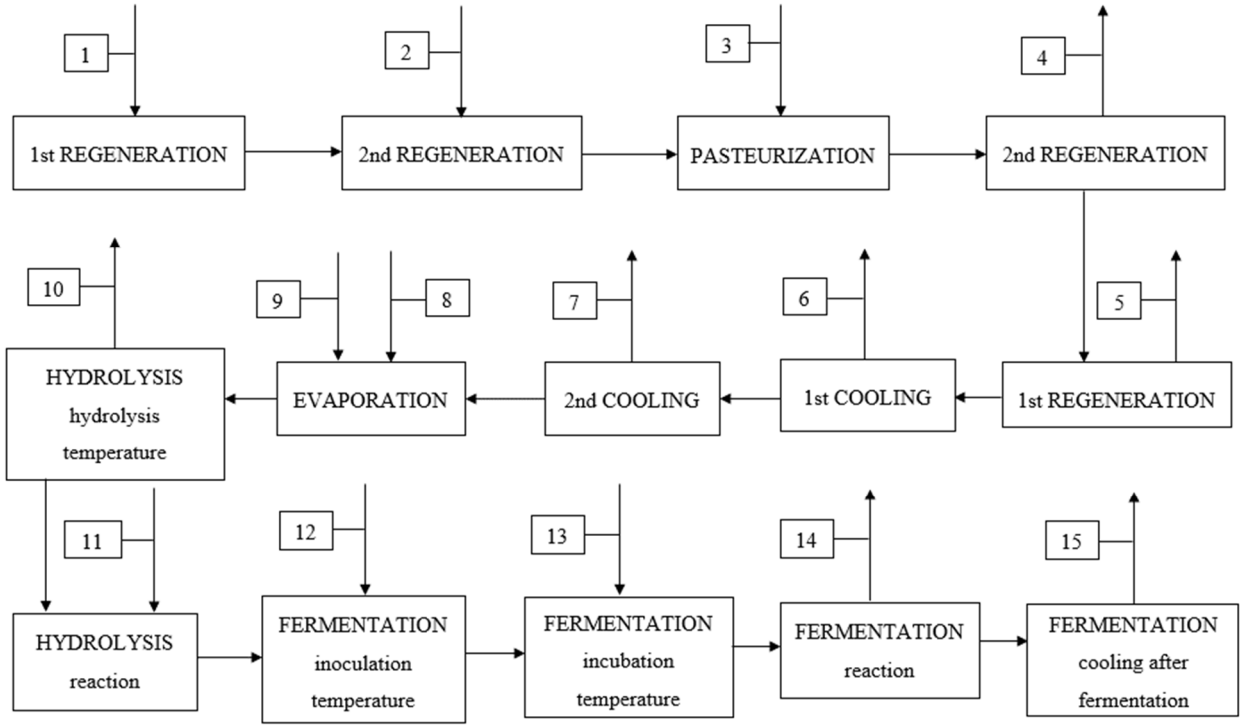

Figure 2. *Process scheme – enthalpy balance.*

to the pasteurization temperature. The flow 4 represents the heat which is removed from the milk in the second regeneration section, following flow 5 represents removed heat in the first regeneration section of the pasteurization unit. The flow 6 represents the heat removed during the first cooling, the flow 7 is the heat removed during the second cooling. Essential heat for evaporation is represented by the flow 8. The heat essential for heating the milk to the temperature of evaporation is represented by the flow 9. The flow 10 represents the heat necessary for cooling the milk to the temperature of hydrolysis. Hydrolysis is an endothermic process. An endothermic process is a process which requires energy. The heat is supplied to the milk to avoid the cooling of the milk and to maintain the temperature of hydrolysis. The flow 12 represents the heat for heating the milk to the temperature of inoculation. The flow 13 represents the heat necessary for heating the milk to the temperature of incubation. Fermentation is an exothermic reaction which means energy is released during the reaction. The flow 14 represents the heat for cooling the milk due to the exothermic reaction. The flow 15 represents the heat removed from the yoghurt during its cooling.

Table 2. *Yoghurts made from hydrolyzed milk - enthalpy balance.*

Flow	Process	Enthalpy	Unit
1	1st regeneration	24,338.71	kJ/batch
2	2nd regeneration	15,667.79	kJ/batch
3	pasteurization	9,472.81	kJ/batch
4	2nd regeneration	-15,667.79	kJ/batch
5	1st regeneration	-24,338.71	kJ/batch
6	1st cooling	-6,084.68	kJ/batch
7	2nd cooling	-6,693.15	kJ/batch
8	evaporator - evaporation	121,329.53	kJ/batch
9	evaporator – heating of the milk	163,910.69	kJ/batch
10	cooling to the temperature of hydrolysis	-17,146.22	kJ/batch
11	hydrolysis – endothermic reaction	6.79	kJ/batch
12	fermentation – inoculation temperature	3,305.91	kJ/batch
13	fermentation – incubation temperature	1,656.80	kJ/batch
14	fermentation – exothermic reaction	-1,756.43	kJ/batch
15	fermentation – cooling after fermentation	-15,227.57	kJ/batch

For the flows 1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 13 and 15 exchanged heat can be expressed by the equation (1).

$$Q = mc\Delta T \quad (1)$$

Specific heat capacity of the flows 1, 5, 6, 7 is 3,900 J/kgK. Specific heat capacities of the flows 2, 3, 9, 10, 12, 13, 15 is calculated by the equation (2).

$$c = 3{,}932 + 1.5T - (22.78 - 0.0624)x_f \quad (2)$$

The temperature T is calculated as the average of the input and output temperature of the milk.

The amount of the heat of the flow 4 is equal to the amount of the heat in the flow 2. The amount of the heat in the flow 11 is calculated based on [3] and the amount of the heat in the flow 14 is calculated based on [4].

1.2. Yoghurts made from plant-based coconut milk

1.2.1. Manufacturing process

Firstly, the mixture is prepared (coconut milk is mixed with tapioca starch). Tapioca starch is used for thickening the mixture. The mixture of coconut milk and tapioca starch is heated to 38 °C (inoculation temperature), yoghurt starter is added into the mixture which is heated to 42 °C (incubation temperature). The mixture incubates for 10 hours. The resulting product – plant-based coconut yoghurt – is cooled to 5 °C. The yoghurt is filled into paper cups. The volume of a paper cup is 0.215 l.

1.2.2. Mass and enthalpy balance

Mass balance is summarized in Table 3.

Table 3*. Yoghurts made from plant-based coconut milk – mass balance.*

Flow	Material	Mass	Unit
1	coconut milk	150.0	kg/batch
2	tapioca starch	16.8	kg/batch
3	coconut milk + tapioca starch	166.8	kg/batch
4	mixture – inoculation temperature	166.8	kg/batch
5	starter culture	0.0	kg/batch
6	inoculated mixture	166.8	kg/batch
7	mixture – incubation temperature	166.8	kg/batch
8	yoghurt	166.8	kg/batch
9	yoghurt after cooling	166.8	kg/batch
10	yoghurt - packaging	166.8	kg/batch
11	yoghurt - labeling	166.8	kg/batch
12	yoghurt - storeroom	166.8	kg/batch

All processes are considered to be isobaric. It means the enthalpy is equal to the heat. Enthalpy balances are summarized in Table 4. The minus sign before the value represents the removed heat, the plus sing before the value represents the supplied heat.

Table 4. *Yoghurts made from plant-based coconut milk – enthalpy balance.*

Flow	Process	Enthalpy	Unit
1	heat – inoculation temperature	22,018	kJ/batch
2	heat – incubation temperature	2,669	kJ/batch
3	cooling of the yoghurt	-24,686	kJ/batch

2. Economic evaluation

2.1. Yoghurts made from hydrolyzed milk

The annual production of the yoghurt is 27,043 kg (respectively 520 kg per week). The factory produces 122,200 packages of the yoghurt per year.

2.1.1. Prices and quantity of raw materials including energy price

The prices are wholesale. Raw material consumption is great and continuous. Prices of raw materials and energy are summarized in Table 5.

Table 5. *Yoghurts made from hydrolyzed milk – prices of raw materials and energy.*

Material	Price	Unit	Reference
skimmed milk	6	CZK/kg	[5]
40% cream	6	CZK/kg	[5]
enzyme	1,000	CZK/kg	[6]
starter culture	256	CZK/package	[7]
paper cup with a lid	2	CZK/piece	[8]
labels	56	CZK/reel	[9]
electricity	2.20	CZK/kWh	[8]
CIP - chemicals	216	CZK/batch	[8]
heat from the boiler room	1.44	CZK/kWh	[8]

2.1.2. Price and quantity of the product

The product is lactose-free yoghurt made from hydrolyzed milk. The volume of a paper cup filled with yoghurt is 0.215 l. The price of a package is 28 CZK.

2.1.3. Fixed capital investment

The investment amount is 4,998,793 CZK. The project is covered by the loan. The amount of the loan is 3 million CZK. The interest period of the loan is 5 years and the interest rate is 8.5 %. The summary of all investments is

given in Table 6. Prices are set according to [8], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19] and [20].

The prices of the falling film evaporator and the pasteurization unit are determined on the basis of the heat exchange surface and the price per square meter of the heat exchange surface.

***Table 6**. Yoghurts made from hydrolyzed milk – fixed capital investment.*

Item	Price [CZK]
Technology	4,306,320
Design and engineering activities	454,435
Project reserve	238,037
Total fixed capital investment	**4,998,793**

2.1.4. Floating investment

Floating investment is equal to direct operating costs per week. Floating investment is 40,107 CZK.

2.1.5. Operating costs

Operating costs are directly related to production over the lifetime and are divided into direct, indirect and distribution. Direct operating costs include raw materials, energy, personal expenses, operator supervision, maintenance costs, consumables and reserve. Indirect operating costs include insurance and share of corporate overhead. The value of the insurance was fixed as 0.5 % of fixed capital investment and overhead as 15 % of maintenance costs and operator supervision and 50 % of maintenance costs. Distribution costs are calculated as 2% income from the sale of the product. The income tax is 19 %. The discount rate is 8 %. Direct operating costs are summarized in Table 7. Total direct operating costs are 2,085,575 CZK/year. The indirect operating costs are 201,657 CZK/year. The insurance is 24,994 CZK/year. The share of corporate overhead is 177,663 CZK/year. The distribution costs are 68,432 CZK/year.

***Table 7.** Yoghurts made from hydrolyzed milk – direct operating costs.*

Material	Price	Unit
raw materials	576,860	CZK/year
energy	213,092	CZK/year
personal expenses	1,157,760	CZK/year
operator supervision	0	CZK/year
maintenance costs	39,990	CZK/year
consumables	56,160	CZK/year
reserve	47,711	CZK/year

Raw materials include skimmed milk, 40% cream, enzyme, starter culture, paper cups with a lid (0.215 l) and labels. The annual cost of each raw material is listed in Table 8.

***Table 8.** Yoghurts made from hydrolyzed milk – annual raw material costs.*

Material	Price	Unit
skimmed milk	240,646	CZK/year
40% cream	2,742	CZK/year
enzyme	13,000	CZK/year
starter culture	69,230	CZK/year
paper cup with a lid	244,400	CZK/year
labels	6,843	CZK/year

Total power consumption for factory operation includes the energy needed to heat the water which is necessary for milk pasteurization (natural gas energy source, 87% efficiency [8], 10% distribution losses [8]), cool cold water, which is heated by the cooling of the milk in the 1st cooling section of the pasteurization unit (cooling factor 2.7 [8], 10% distribution losses [8]), cool ice water, which is heated by the cooling of the milk in the 2nd cooling section of the pasteurization unit (cooling factor 2.7 [8], 10% distribution losses [8]). Power consumption includes the heat needed to run the evaporator (natural gas power source, 87% efficiency, 10% distribution losses), cooling of the milk to hydrolysis temperature (cooling factor 2.7), heating of the milk to inoculation temperature and to incubation temperature (electricity power source, 95% efficiency [8]) and cooling of the yoghurt (cooling factor 2.7). The heat needed to eliminate the effect of an endothermic and exothermic reaction is also included (electricity power source, 95% efficiency, cooling factor 2.7). The price of energy includes the price of energy needed to run pumps and vacuum pumps as well.

Staff costs include salaries for factory employees (4 employees) + social (25 %) and health insurance levies of the employer (9 %). Consumables include chemicals necessary to sanitize equipment. The reserve is calculated as 2 % of direct operating costs.

2.1.6. Project financing and loan

The current owner of the factory is the investor of the project. The amount of the loan is 3 million CZK. The interest period of the loan is 5 years and the interest rate is 8.5 %.

2.1.7. Depreciation

Machines and equipment belong to the 2nd depreciation group with a depreciation period of 5 years. Depreciation in the first year is 11 % and depreciation in the following years is 22 %. The input price for the calculation of the depreciation is 4,306,320 CZK. The depreciation amounts for each year are summarized in Table 9.

***Table 9**. Yoghurts made from hydrolyzed milk – depreciation.*

Depreciation	Amount	Unit
depreciation in the 1st year	473,695	CZK/year
depreciation in years 2 to 5	958,156	CZK/year

2.1.8. Payback period

Payback period is 5 years.

2.1.9. Discounted payback period

Discounted payback period is 7 years.

2.2. Yoghurts made from plant-based coconut milk

The annual yoghurt production is 43,368 kg (834 kg per week). The factory produces 182,000 packages of the yoghurt per year.

2.2.1. Prices and quantity of raw materials including energy price

The prices are wholesale. Raw material consumption is great and continuous. Prices of raw materials and energy are summarized in Table 10.

***Table 10.** Yoghurts made from plant-based coconut milk – prices of raw materials and energy.*

Material	Price	Unit	Reference
coconut milk	76	CZK/l	[8]
tapioca starch	73	CZK/kg	[8]
starter culture	256	CZK/package	[7]
paper cup with a lid	2	CZK/piece	[8]
labels	56	CZK/reel	[8]
electricity	2.20	CZK/kWh	[8]
CIP - chemicals	216	CZK/batch	[8]

2.2.2. Price and quantity of the product

The product is yoghurt made from plant-based coconut milk. The volume of a paper cup filled with yoghurt is 0.215 l. The price of a package is 31 CZK.

2.2.3. Fixed capital investment

The investment amount is 1,087,255 CZK. The project is covered by the loan. The loan amount is 1 million CZK. The interest period of the loan is 5 years and the interest rate is 8.5 %. The summary of all investment is given in Table 11. Prices are set according to [8], [10], [13], [15], [18], [19] and [20].

***Table 11.** Yoghurts made from plant-based coconut milk – fixed capital investment.*

Item	Price [CZK]
Technology	936,640
Design and engineering activities	98,841
Project reserve	51,774
Total fixed capital investment	**1,087,255**

2.2.4. Floating investment

Floating investment is equal to direct operating costs per week. Floating investment is 97,835 CZK.

2.2.5. Operating costs

Operating costs are directly related to production over the lifetime and are divided into direct, indirect and distribution. Direct operating costs include raw materials, energy, personal expenses, operator supervision, maintenance costs, consumables and reserve. Indirect operating costs include insurance and share of corporate overhead. The value of the insurance was fixed as 0.5 % of fixed capital investment and overhead as 15 % of maintenance costs and operator supervision and 50 % of maintenance costs. Distribution costs are calculated as 2% income from the sale of the product. The income tax is 19 %. The discount rate is 8 %. Direct operating costs are summarized in Table 12. Annual total direct operating costs are 5,087,416 CZK/year. The annual indirect operating costs are 179,753 CZK/year. The annual insurance is 5,436 CZK/year. The annual share of corporate overhead is 174,316 CZK/year. The annual distribution costs are 112,840 CZK/year.

***Table 12.** Yoghurts made from plant-based coconut milk – direct operating costs.*

Item	Price	Unit
raw materials	3,756,896	CZK/year
energy	6,154	CZK/year
personal expenses	1,157,760	CZK/year
operator supervision	0	CZK/year
maintenance costs	8,698	CZK/year
consumables	56,160	CZK/year
reserve	101,748	CZK/year

Raw materials include coconut milk, tapioca starch, starter culture, paper cups with a lid (0,215 l) and labels. The annual cost of each raw material is listed in Table 13.

Table 13. *Yoghurts made from plant-based coconut milk – annual raw materials costs.*

Material	Price	Unit
coconut milk	2,964,000	CZK/year
tapioca starch	318,864	CZK/year
starter culture	99,840	CZK/year
paper cup with a lid	364,000	CZK/year
labels	10,192	CZK/year

Total power consumption for factory operation includes the energy needed to heat the mixture to inoculation temperature (electricity power source, 95% efficiency), heat the mixture (electricity power source, 95% efficiency) to the incubation temperature, cool the mixture (yoghurt) after incubation (cooling factor 2,7) and the energy required to run the pumps.

Staff costs include salaries for factory employees (4 employees) + social (25 %) and health insurance levies of the employer (9 %). Consumables include chemicals necessary to sanitize equipment. The reserve is calculated as 2 % of direct operating costs.

2.2.6. Project financing

The current owner of the factory is the investor of the project. The amount of the loan is 1 million CZK. The interest period of the loan is 5 years and the interest rate is 8.5 %.

2.2.7. Depreciation

Machines and equipment belong to the 2nd depreciation group with a depreciation period of 5 years. Depreciation in the first year is 11 % and depreciation in the following years is 22 %. The input price for the calculation of the depreciation is 936,640 CZK. The depreciation amounts for each year are summarized in Table 14.

Table 14. *Yoghurts made from plant-based coconut milk – depreciation.*

Depreciation	Amount	Unit
depreciation in the 1st year	103,030	CZK/year
depreciation in years 2 to 5	208,402	CZK/year

2.2.8. Payback period

Payback period is 5 years.

2.2.9. Discounted payback period

Discounted payback period is 7 years.

3. What-if analysis

What-if analysis focuses on one parameter – the price of the product. The what-if analysis is shown in Figures 3 and 4.

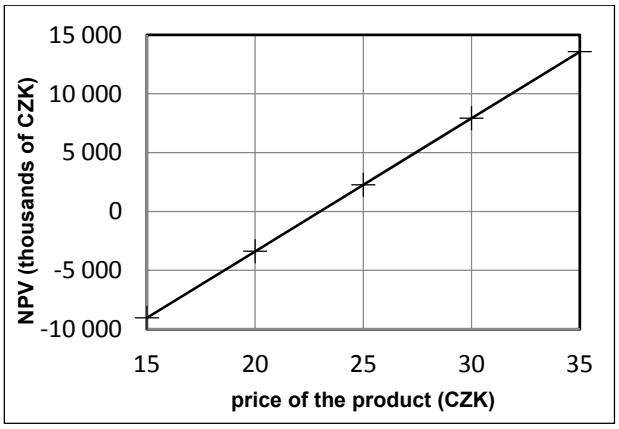

Figure 3. *Yoghurt made from hydrolyzed milk – price of the product.*

Figure 4. *Yoghurt made from plant-based coconut milk – price of the product.*

4. Conclusion

In the work the processes of manufacturing lactose-free yoghurt made from hydrolyzed milk and yoghurt made from plant-based coconut milk are described for an existing factory of milk products which wants to expand its production due to increasing demand for lactose-free and vegan products. The work includes mass and enthalpy balances, economic evaluation of the projects and what-if analysis of selected parameter.

Payback period of the project (yoghurt made from hydrolyzed milk) is 5.47 years, return on investment is 14.74 %, net present value is 5,665,391.27 CZK, internal rate of return is 18.90 % and internal rate of return resources is 23.89 %. Final price of the product is 28 CZK per package. The annual production of the yoghurt is 122,000 packages. The price of the product is higher than the prices of other products which are available at the Czech market. Yoghurts made from hydrolyzed milk are not competitive at the Czech market due to its high price. The reasons why the price of the product is so high could be following: production line includes a new pasteurization unit, falling film evaporator and homogenizer which means the total cost is higher due to the purchase of the equipment. Lower project reserve, eventually floating investment and distribution paid from the current supplies

of the factory, could reduce the price of the product. If the new equipment is not acquired the price of the product will be substantially lower – the product will cost 20.20 CZK.

Payback period of the project (yoghurts made from plant-based coconut milk) is 5.26 years, return on investment is 15.48 %, net present value is 1,427,720.68 CZK, internal rate of return is 19.57 % and internal rate of return resources is 31.05 %. Final price of the product is 31 CZK per package. The annual production of the yoghurt is 182 000 packages. This product is competitive at the Czech market.

Acknowledgment

I would like to express my deep gratitude to Ing. Jaromír Štancl, PhD., for his patient guidance, enthusiastic encouragement and useful critiques of this work.

List of Symbols

Q heat (J)
m mass (kg)
c specific heat capacity (J/kgK)
T temperature (°C)
x_f fat content (%)

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