3rd International Conference on Advanced Research in Supply Chain Management

May 19-21, 2023

SupplyChain Management

Milan, Italy

Mathematical Modeling and Optimization of Dairy Waste Scum-Based Biodiesel Supply Chain Under the Paradigm of Sustainability: Part 2 Total Production Size of The Material Flows on The Bulgarian Scale

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Abstract

Biodiesel is an environmentally friendly alternative to petro-diesel. The production of biofuels and the use of biodiesel make it possible to reduce the harmful emissions released when using traditional diesel. In this paper is applied the mixed integer linear programming (MILP) model for dairy waste scum-based supply chain for biodiesel, as is proposed in Part 1. In the case under consideration, Bulgaria is territorially divided into 27 regions corresponding to its provinces. The supply chain investigated in this work consists of 12 regions - a potential location center for farms (milk producers), 12 milk processing regions, 5 potential locations for biorefineries and 27 customer areas. In the mathematical model, as feedstock for biodiesel production, it is assumed that waste biomass generated in the production of four types of milk products (yogurt 4.5%, milk 3%, yellow cheese and white brine cheese) can be used, obtained from only from cow's milk. This part of the study details the constraints that must be met to achieve the objective of minimizing economic costs while meeting environmental requirements. In this study are shown the results in terms of total production size of the different material flows. The mathematical model is developed in terms of GAMS, and it can be used as a complete decision for other regions or countries by modification of specific data.

Keywords: biofuel, energy efficiency, MILP, optimal design, dairy production

1. Introduction

In recent years, the use of diesel has increased dramatically, and biodiesel can be considered an alternative fuel to petroleum diesel. Another fact is that fuel supplies are gradually decreasing, and this can lead to shortages and an increase in their prices. The usage of petroleum fuels also leads to air pollution with harmful emissions, which increases the greenhouse effect. The biodiesel as a substitute for diesel has the following advantages (Jaichandar & Annamalai, 2011):

- The biodiesel can be used without any modifications in existing engines;
- The biodiesel does not contain harmful compounds such as: the aromatic hydrocarbons, metals, crude oil residues and sulfur;
- The biodiesel (which is an oxygenated fuel) results in lower soot and carbon monoxide emissions compared to the diesel;
- The use of biodiesel does not lead to an increase in global warming because the carbon dioxide released during its combustion is reabsorbed by plants. And these plants would be feedstocks for the production of biodiesel. Therefore, the CO_2 balance remains unchanged;
- The biodiesel is more lubricating compared to the petroleum diesel and its use would extend the life of the diesel engines;
- Biodiesel is produced from renewable vegetable oils/animal fats and hence improves energy security and economy independence.

Depending on the feedstocks for biodiesel production, it is divided into: first, second and third generation biodiesel.

The biodiesel from first generation is produced from the feedstocks as edible vegetable oils. The most commonly used are: sunflower, coconut, soybean, peanut, rapeseed and palm. The biodiesel production from edible vegetable oils is easier because they are more widely available. The production of biodiesel from the edible vegetable oils leads to the solution of several ethical problems, because these raw materials represent competition to the food industry (Knothe & Canon, 2017).

Second generation biodiesel is obtained from the waste oils and the fats. These raw materials are inedible and non-competing with the food industry. These inedible biomasses are: the waste cooking oils (WCOs); greases and waste animal fats (WAFs), and the waste oily streams from the oil refinery (Zivkovic et al., 2017). The WCO represents the waste oils and animal fats previously used for frying potatoes, fish, etc. The waste fats are divided into yellow and brown fats depending on their Free Fatty Acids (FFA) content. The brown fats have a FFA of more than 15% while, yellow fats less than 15% (Canakci, 2007). The waste animal fats and grease (WAFs) are: a lard, a fish oils, a tallow and a poultry fat (Bankovic-Ilic et al., 2014). The waste oils and the fats are cheap feedstock, which leads to the reduction of production costs. They do not compete with the food industry and lead to the reduction of this type of waste (Dias et al., 2008, A).

The biodiesel produced from algae is third generation.

The biodiesel produced from different feedstocks has the same chemical and physical properties (Dias et al., 2008, B).

The production of biodiesel is the transesterification of oils with alcohols through catalytic reactions, and as a result, it produces the waste product glycerol and the biofuel-fatty acid methyl esters (FAME).

For this reason, the biodiesel can also be produced from the oils/fats remaining in the wastewater from dairy plants. The waste biomass (dairy waste scum (DWS)) from dairy plants can be used as a raw material for the production of the biodiesel. The DWS has a high triglyceride content (more than 80 %) (Kavitha et al., 2019). The dairy waste scum possesses the following advantages:

- The DWS will be delivered throughout the year continuously;
- We can make an estimate of the amount of used the dairy waste scum;
- The DWS can reduce the overall production cost;
- The free fatty acid content is lower in the DWS and therefore the direct transesterification would be sufficient for the biodiesel production (Yathish et al., 2013).

The price and quality of the biodiesel is determined by the type of feedstock used, the production and storage technologies, the location of the biorefineries, as well as the logistics. For example, some researches (Ahn et al., 2015) investigated the use of microalgae biomass as feedstock for the biodiesel production. They develop a deterministic mathematical model to design of biodiesel supply chains from microalgae. The model proposed by the authors determines the location of supply centers in order to minimize total costs. Another study (Babazadeh et al., 2019) also develops a chain network design model to minimize total supply chain costs. One of the first study (Habib et al., 2020) on biofuels produced from animal waste fat develops a sample for dynamic optimization for Biofuel Supply Chains (SCB). To extend the tactical and strategic decisions (in the production of the biodiesel from a waste animal fat), a multi-objective optimization procedure is set, then a compromise option is sought that would satisfy the environmental, social and economic activities of the supply chains for the biodiesel (a cow and a sheep tallow, as well as waste fatty from a chicken).

2. Problem definition

This study examines the integration of a dairy supply chain into the biodiesel supply chain as a continuation of our other study (Nikolova et al., 2023). The proposed supply chain includes the dairy farms for production of different the milks; dairy plants for production of different type of milk products (yogurt 4,5 %; fresh drinking milk 3 %; yellow cheese and white brined cheese) according known technologies (recipes); the customers of the end dairy products and the biorefineries for utilization of a dairy waste scum according known technology.

The territory of Bulgaria divided into 27 regions, with each region representing a potential customer area, 12 are the regions for receiving biomass/wastewater from milk plants, 12 regions as a potential center for locating farms and the optimal regions for building biorefineries are 5. The 10-year operating life of the biodiesel production plant is assumed.

The task that is solved with the program package of the Gams 31.2.0 is to find the optimal conditions for the operation of the considered supply chain in order to minimize the economic costs while complying with the environmental requirements. The task is formulated in conditions of a Mixed Integer Linear Programming (MILP). A detailed description of the formulated optimization problems, all mathematical models, constraints, and optimization criteria are given in the study of Ivanov et al., 2022.

2.1 Constraints

The constraints that must be met in order to ensure the optimization set is obtained are defined as linear functions of all decision variables. They are:

The constraints for the production capacity of a biodiesel production plant:
The productivities per year of the biodiesel production plant are defined in upper and lower boundaries.

The constraints providing admissibility of the flows:

These constraints guarantee the permissible values of the waste flows in the processing of milk (a dairy waste scum - DWS) from each of the regions of their production to the place of their use.

The constraints providing that the needs of all regions of the dairy products will be met.

The constraints providing the necessary amounts of milk for the production of the dairy products.

The logical constraints.

The constraints providing that in a given region $f \in F$ *only one biorefinery with production yield* $p \in P$ *will be built for produce of biodiesel:*

These constraints inform that only one production capacity $p \in P$ can be chosen for each equipment $f \in F$ in the region.

The constraints provide that there is only one connection route between the region for DWS production and the region for the use of biodiesel.

The constraints provide that only one type of transport is used for the transportation of intermediate, feedstocks, and end products from one given place to another:

1/ The constraint providing that a given type of DWS will be transported from a given dairy to a given biodiesel production plant using only one type of transport;

2/ The constraint providing that a given type of feedstock (fresh milk) will be transported from a given farm to a given dairy plant using only one type of transport;

3/ The constraint providing that a given type of dairy product will be transported from a given dairy plant to a given customer using only one type of transport.

The transportation constraints.

The constraints providing that a produced DWS from dairy will be used for the produce of a biodiesel.

The constraints for the satisfaction of the material balance of the combined supply chain.

The constraints for the satisfaction of the annual demand of the dairy plant.

Constraints providing $n \in N$ *(maximum annual production yield of the farm) for the production of milk of type* $k \in K$ *type, (t /y)*

The admissibility of flows is given by constraints.

2.2 Optimization criterion

The integrated supply chain for a dairy and biodiesel supply chain is optimally designed with a model incorporating an economic optimization criterion that gives the sum of the annual costs of building and operating the combined supply chain. The latter includes the annual government incentives, the greenhouse gas emission costs, the annual operating costs, and the total annual capital costs ($). The optimization criterion is subjected to minimization. The environmental impact of the supply chain is represented as a constraint. The determination of the optimal location of the biodiesel production plants in the regions and their parameters is formulated with the following optimization task:

$$Find\!: X_t[Decision\ \text{variables}]\ MINIMIZE\{COST(T_t)\ \}\ s.t.\!:\{Constraint\ s\} \quad (1)$$

$$COST = \sum_{t \in T}(LT_t TDC_t) \quad (2)$$

where,

LT_t is the duration of time intervals $t \in T$, (y);

TDC_t is the total value for the supply chain, ($).

The objective function and all constraints are linear functions of all decision variables.

3. Input date

In this section of the presented study, some of the data used are given.

- *Data on the raw material used for the biodiesel production*

Large dairies use a wide range of installations and equipment to process, pack, store, and transport different types of fresh milk and milk products. The wastewater during production and packaging is a large amount, and it is treated and collected in treatment plants. The wastewater recycling results in dairy waste scum (DWS) with a cloudy white color. It usually contains a mixture of lipids, fats, packaging materials, proteins and etc. The composition of the resulting dairy waste was analyzed using gas chromatography (Anbarasu & Renganathan, 2011). The physical-chemical properties of this biomass give reason to consider DWS as a potential feedstock for produce of the biodiesel. The extraction of lipids from dairy wastewater scum and their conversion to biodiesel under different reaction conditions was analyzed. The esterification/transesterification of residual lipids has been shown to be the most efficient approach for the biodiesel production (Abreu-Jaureguí et al., 2023).

In the mathematical model considered in this study, as a source for obtaining biodiesel, it is assumed that waste biomass generated in the production of four types of the dairy products (yellow cheese, fresh milk 3%, white brine cheese and yogurt 4.5%) can be used.

- *Data on the location and production capacity of farms, dairies, and biorefineries, and data on the actual delivery distance among provinces in Bulgaria for different types of transport*

The locations and productivity of the farms (https://www.agrostat.bg/ISASPublic/Livestock), dairy plants (http://old.europe.bg/htmls/page.php?id=7010&category=247) biorefineries and the type of transport between them, are known.

The lengths in kilometers between urban areas in Bulgaria (for each type of transport) for the purposes of this study were taken from the National Transport Agency (www.rta.government.bg).

The amount of fresh milk that is produced by the dairy farms (given in Table 1) is theoretically calculated based on the characteristics of some dairy breeds of cows. For the calculation of the minimum milk yield of one cow for one day is taken - 11 kg/day, and for the maximum – 30 kg/day. The normal lactation period of the cows is an average of 300 days-per year, and the calculations for the productivity of dairy farms are made with this data in mind.

Table 1: Characteristics of some dairy breeds of cows (https://bg.farmafans.ru)

Breed	**Daily yield of milk, (kg)**	**Fat content, %**
Kholmogory	15-17	3.9
Holstein	25-30	3.8
Red & White	18-28	2,5-3
Red steppe	11-13	3.5
Yaroslavl	13-20	4.15
Ayrshire	13-26	4.5

- *Data on the price of milk as a raw material and on-farm productivity*

Information for a milk price and the productiveness of dairy farm are demonstrated in Table 2:

Table 2: The price of milk and the productiveness of dairy farm

№	**Name of Region**		**Price of milk sold to companies** $UNMK_{nmkt}$	**Minimum amount of milk produced by the farm** PN_{knt}^{MIN}	**Maximum amount of milk produced by the farm** PN_{knt}^{MAX}
			$[\$/ton]$	$[ton/day]$	$[ton/day]$
1	Region_3	Dobrich	450	11,847	32,310
2	Region_4	Gabrovo	457	4,840	13,200
3	Region_5	Haskovo	444	2,343	6,390
4	Region_6	Kardzhali	450	2,838	7,740
5	Region_10	Pazardzhik	450	4,664	12,720
6	Region_13	Plovdiv	463	23,254	63,420
7	Region_17	Silistra	457	10,373	28,290
8	Region_18	Sliven	450	12,815	34,950
9	Region_20	Sofiya	463	5,588	15,240
10	Region_24	V. Tarnovo	450	8,173	22,290
11	Region_26	Vraca	450	4,015	10,950
12	Region_27	Yambol	450	2,717	7,410

It is assumed that each farm sells the milk to the dairies at a price of 450 $[\$/ton]$. The minimum annual capacity of farms PN_{knt}^{MIN} is assumed to be 0 $[ton/day]$.

- *The costs of capital and production yield of the biodiesel production plant*

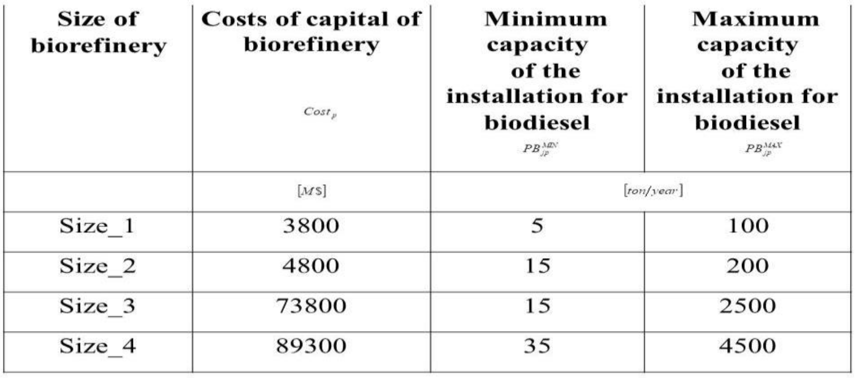
The refinery costs of capital represent are fixed and variable. The variable costs of capital for converting feedstock into biodiesel are affected by the size of the plants and do not depend on the technology for production of the biodiesel, because it is standard. The value of variable capital expenditure is scaled using the study (Ozlem et al., 2012).

$$\frac{Cost_p}{Cost_{base}} = \left(\frac{Size_p}{Size_{base}}\right)^R \tag{3}$$

where $Cost_p$ *and* $Size_p$ are costs of investment and the yield of the biorefinery, respectively a new plant. $Cost_{base}$ *are* the known investment costs for a certain capacity of the plant $Size_{base}$ and R is a scaling factor. The scaling factor R is usually between 0.6 and 0.8 (Remer & Chai, 1990).

The nonmoving costs of capital vary depending on the placement of the biorefineries. The total specific investment costs for the biodiesel production plants as a function of plant size are given in Table 3.

Table 3: Total specific investment costs for biodiesel production plants as a function of plant size (Ozlem et al., 2012), (Giarola et al., 2011)



Size of biorefinery	Costs of capital of biorefinery $Cost_p$	Minimum capacity of the installation for biodiesel PB_{jp}^{MIN}	Maximum capacity of the installation for biodiesel PB_{jp}^{MAX}
	$[M\$]$	$[ton/year]$	
Size_1	3800	5	100
Size_2	4800	15	200
Size_3	73800	15	2500
Size_4	89300	35	4500

The capital costs of biorefineries for each region are determined by Equation:

$$Cost_{pf}^{F} = M_f^{\mathrm{cost}} Cost_p, \forall p \in P, \forall f \in F \tag{4}$$

M_f^{cost} is correction factor in the price of biorefineries in $f \in F$ (a region) as installed $M_f^{cost} \geq 1$. The different geographical area has a different coefficient value. It takes into account indicators such as labor costs, land price, etc.

- *Data on transport costs for a milk, milk products and waste biomass*

Based transportation network is introduced in the calculation of the raw material and fuel transportation costs of the supply chain. The calculating the shortest distances between the regions for: biomass, plants for biodiesel and customer areas are done using this transport network. It is assumed that all transport will be carried out by land routes.

Transport costs for the feedstocks are described in (Ivanov et al., 2013), (Ivanov et al., 2018).

- *Date on environmental parameters used in the research*

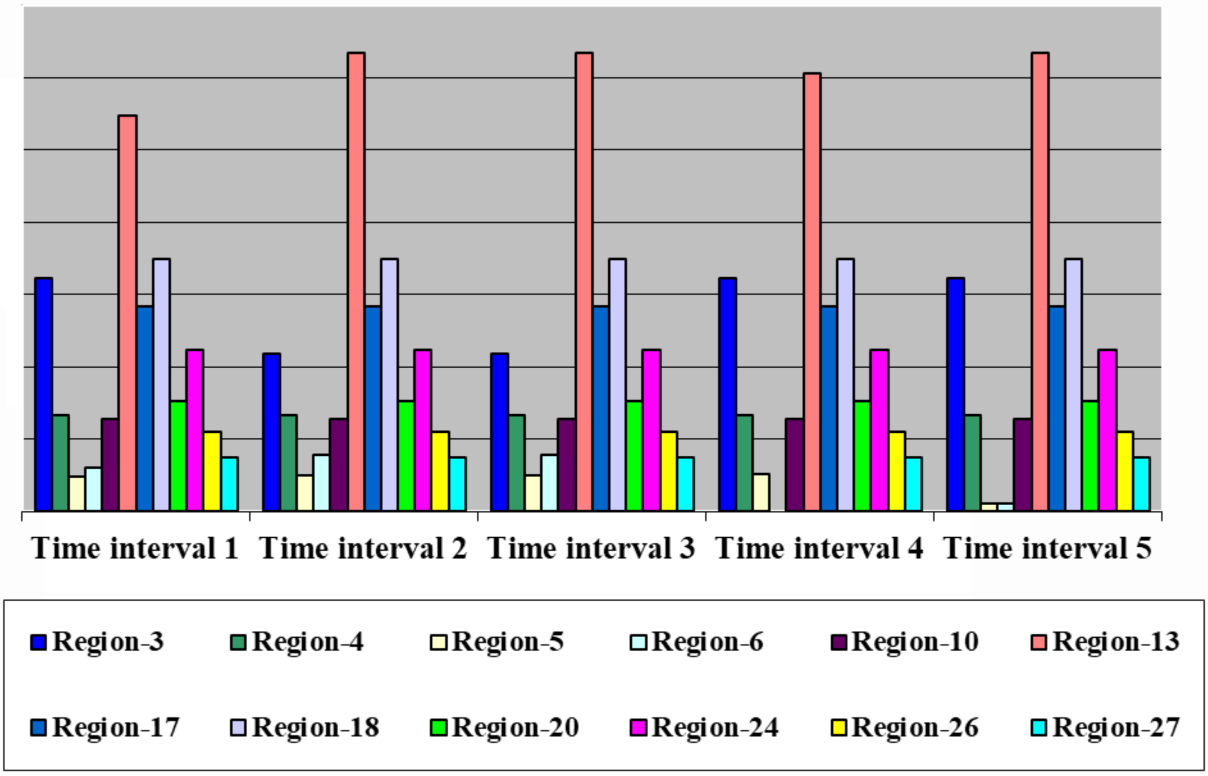
We use in this study the average emission factors that are recommended in other studies (European Commission, 2006), (Edwards-Jones et al., 2008).

4. Results

4.1 Total amount of cow's milk production, as raw material, distributed by regions

Figure 1 summarizes the results of applying the proposed optimization approach. This approach gives the total amount of cow's milk produced for a raw material and its distribution by the respective regions.

Figure 1: Total amount of cow's milk production, as feedstock, distributed by regions, [ton/d]

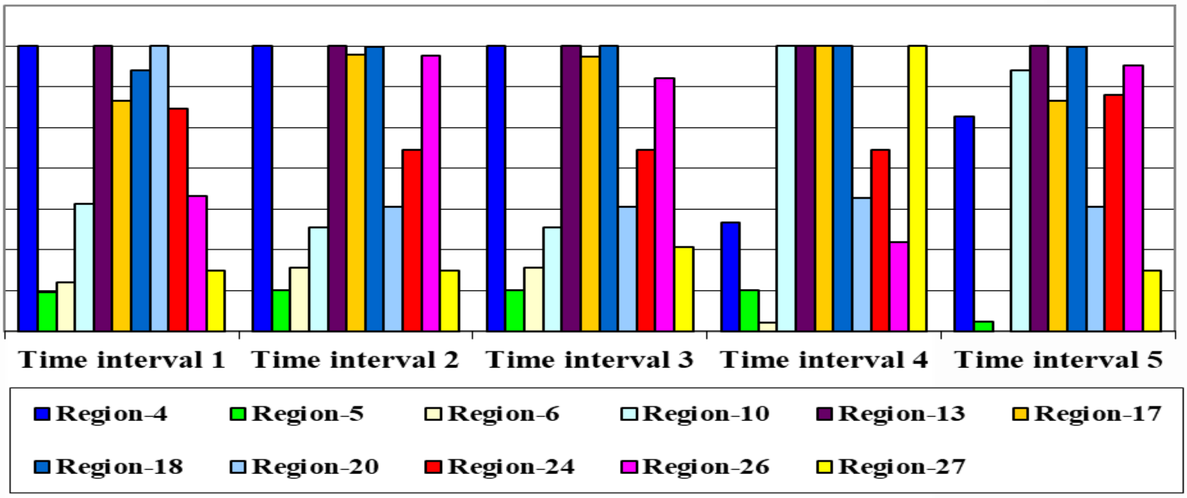


The analysis of a Figure 1 shows that the largest total amount of cow's milk is generated at region 13 during all of the time intervals. The least total amount of cow's milk, as feedstock, is generated at regions 5 and 6 during all of the time intervals.

4.2 Total amount of production of final dairy products, distributed by region

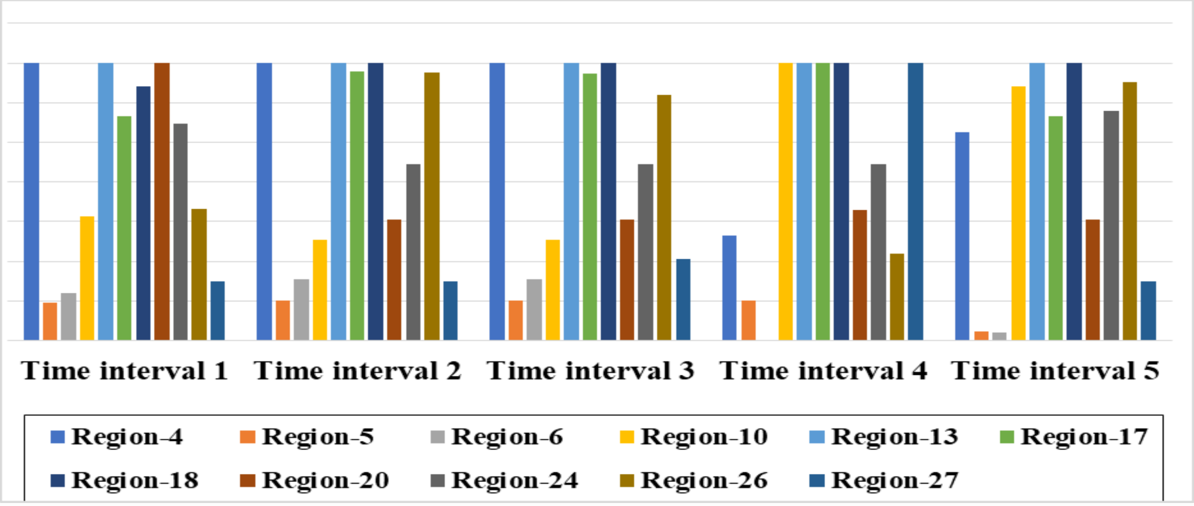
Figure 2 shows the total amount of drinking milk (3%) produced and distributed by the respective regions. The analysis of Figure 2 shows that the least total amount of drinking milk, 3 % (as the final dairy product), is produced at regions 5 and 6 during all of the time intervals.

Figure 2: Total amount of production of final dairy products, distributed by region, for milk 3%, [ton/d]



The total amount of production of: a yoghurt 4.5%, cheese and yellow cheese distributed by regions, is summarized in Figure 3. The analysis of Figure 3 shows that the least total amount of yoghurt, 4.5%, cheese, and yellow cheese is produced at regions 5 and 6 during all of the time intervals.

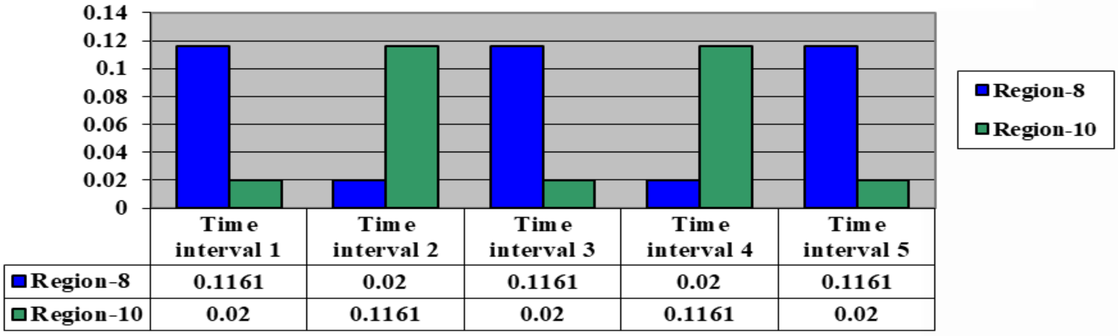
Figure 3: Total amount of production of final dairy products, distributed by region, for yoghurt 4.5%, cheese and yellow cheese, [ton/d]



4.3 Total amount of biomass waste DWS production, distributed by regions

The total amount of dairy waste scum production, distributed by regions, is demonstrated in Figure 4. The analysis shows that during time intervals: 1, 3 and 5 at region 8 dairy waste scum is used in large quantities than in region 10. During time intervals: 2 and 4 in region 8, dairy waste scum was used in smaller quantities than in region 10.

Figure 4: Total amount of biomass waste DWS production, distributed by regions, for milk 3%, [ton/d]



	Time interval 1	Time interval 2	Time interval 3	Time interval 4	Time interval 5
■ Region-8	0.1161	0.02	0.1161	0.02	0.1161
■ Region-10	0.02	0.1161	0.02	0.1161	0.02

5. Conclusion

The need for a sustainable substitute for conventional fuels inevitably leads to an increase in the popularity of the biofuels and, in particular, a biodiesel. The deepening economic, environmental and social crises in various parts of the world leads to an increased demand for alternative fuels, but the issue of expensive feedstocks remains on the agenda. In this regard, the present study proposes a mathematical modeling approach leading to the optimization of dairy waste scum-based biodiesel supply chain under the paradigm of sustainability. An optimization task is formulated, reducing to a linear function to minimize the total logistics costs of the supply system, taking into account fixed, variable and emission costs. The solution was generated using the software package the GAMS, as MILP. Results are presented regarding the total production size of the material flows on the Bulgarian scale.

Depending on the results obtained, it was found that: from an economic point of view, a competitive production for biodiesel depends on the optimization of the entire integrated supply chain over the entire planning horizon. In this study, an approach is proposed that can be applied in the different geographical regions having the capacity to produce this feedstock. With this model, other tasks can be solved regardless of changing policy standards as well as changing technologies in biodiesel production for extended planning periods.

Our other studies on this topic are the following: Mathematical modeling and optimization of dairy waste scum-based biodiesel supply chain under the paradigm of sustainability: Part1: Optimal structure and size of flows on the Bulgarian scale.; Optimal Design of Sustainable Biodiesel Supply Chain Using Dairy Waste Scum as a Feedstock Generated from Dairy

Supply Chain.; and A MILP approach of optimal design of a sustainable combined dairy and biodiesel supply chain using dairy waste scum generated from dairy production. (Boyan. B. I. et al., 2021; 2022).

Acknowledgment

The authors are grateful to the National Science Fund, Ministry of Education and Science of the Republic of Bulgaria, Contract № КП-06-Н37/5/06.12.19, without which this research could not have been carried out.

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