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Optimal Design of Sustainable Biodiesel Supply Chain Using Dairy Waste Scum as a Feedstock Generated from Dairy Supply Chain

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The rapid depletion of fossil fuels and the increased environmental impact of their combustion make it necessary to find cleaner and more sustainable energy resources. Over the last decades, biodiesel has been introduced as an alternative because of its advantages over fossil fuels. However, the high production cost of biodiesel is one of the main obstacles to achieving its commercial viability. One way to improve the efficiency and sustainability of this process is to use Dairy Waste Scum (DWS), which is a waste product from the dairy industry as a feedstock. Selection of the feedstock used is only a part of the strategy to increase the sustainability of this type of production. The most effective way to achieve this is by optimising the activities across the supply chains (SCs). In addition, the sustainability of the biodiesel production process using DWS may be influenced by design of optimal product portfolio of the considered dairy SC. This study proposes an approach for optimal design of a sustainable combined dairy and biodiesel/diesel SC using dairy waste scum as a feedstock, generated from dairy SC. It is based on defining mixed integer linear programming (MILP) model of the optimal design of the considered combined SC. The latter includes economic and environmental assessments. The first one is defined as an optimization criterion while the second one is defined as a constraint. The model takes into account key SC activities such as infrastructure compatibility; the production of the dairy products; milk, dairy products and DWS transportation between the regions, carbon taxes, related with all SC activities. The environmental and economic performance of the combined dairy and biodiesel/diesel SC is assessed by the annual operating costs for the combined SC design and greenhouse gas (GHG) emissions of pollutants associated with its operation. The developed approach was implemented on a real case study from Bulgaria. The analysis of the environmental results shown that the total GHG emissions generated by the operation of the SC for all time intervals are mainly due to the production of the products in dairies and utilization of unused DWS for production of biodiesel.

1. Introduction

The depletion of fossil fuels and the increasingly serious environmental and climate changes in recent years require the search for and use of new renewable energy sources. A good alternative to fossil fuels are biofuels in particular biodiesel due to its advantages over fossil fuels, which include higher ignition temperature, improved lubricity and lower toxicity. Biodiesel can be obtained from a variety of food, non-food and waste sources. The production of biodiesel using cereals can lead to food security problems, which affect food prices. Production of biodiesel from wastes is also becoming more expensive due to the application of expensive technologies for pre-treatment of used feedstocks. The latter, however, is offset by the low cost of feedstocks and their full use, which leads to a reduction of the environmental impact. Waste from the food industry is most often used as feedstocks for biodiesel production. In particular, dairy waste scum can be considered as potential feedstock for biodiesel production due to the high content of triglycerides in them (more than 80 %) (Kavitha et al., 2019). So far research in this field has focused only on determination of the optimal parameters of the transesterification process (catalyst loading, the molar ratio of methanol, reaction temperature and time) which influence the

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biodiesel yield. For example, Krishnamurthy et al., (2020) have improved the efficiency of the biodiesel production process using CaO Sheil as a catalyst. Srikanth et al., (2021) have applied an analysis of variance (ANOVA), to examine the importance of the model parameters of the transesterification process at the 95 % confidence level. Behera et al., (2019) have evaluated the lipid accumulation potential of bacteria isolated from dairy effluent scum as potential biodiesel feedstock. Research has been done on the use of dairy wastewater as a medium for growing microalgae (Swain et al., 2020) which is used as a feedstock for biodiesel production. One way to increase the economic and environmental benefits of biodiesel production is to optimize all activities across the network from the feedstock, through the production itself, to the customer or applying the strategy for optimal design of a sustainable SC. Since biodiesel SC design decisions directly influence social and environmental aspects, SC optimization within the sustainability paradigm is necessary. Ganev et al. (2021) have proposed a MILP optimization model for strategic design of a sustainable Integrated Biodiesel/diesel SC using 1st and 2nd generations feedstock for biodiesel production providing all aspects of the sustainability – economic, environmental and social. Rungphanich and Siemanond, (2019) have proposed a stochastic mixed-integer programming with chance constraints model for design four echelons supply-chain network for biohydrodeoxygenated diesel under uncertainty from both raw materials availability and the demand.
On the other hand, the amounts of the generated DWS in the production of dairy products, which are used as a feedstock for the production of biodiesel, are also influenced by the organisation of the activities in the respective SCs. Such an example is given by Kirilova and Vaklieva-Bancheva (2020) who have been developed an approach for design of optimal product portfolio of dairy SC for the production of different types of dairy products. Bearing in mind the latter, one of way to achieve full sustainability of the biodiesel/diesel production using DWS is if in the optimisation problem for strategic design of biodiesel/diesel SC, the products portfolio of the production of dairy products is involved.
The present study proposes an approach for optimal design of a sustainable combined dairy and biodiesel/diesel SC using DWS as a feedstock, generated from dairy SC. The latter comprises milk suppliers, dairies and markets. The approach aims optimization of products portfolios of the dairies, locations and capacities of processing plants for the use of the DWS, transportation of milk, dairy products and DWS, locations and capacities of the built biorefineries for production of biodiesel, and its transport to the blending centres. For an optimisation criterion the annual operating costs of the SC are selected. The latter is subjected to minimisation at specified environmental impact, technological and time constraints. They include the dairy products production costs, DWS biodiesel production costs and transportation costs. The environmental assessment is related to the amount of GHG emissions generated during operation of the combined dairy and biodiesel/diesel SC.

2. Problem statement

Figure 1 shows a combined dairy and biodiesel/diesel SC using DWS as a feedstock generated from the dairy SC. The presented SC includes a set of milk farms for production of different types of milk (cow, goat, sheep, etc.), a set of plants for production of different dairy products (fresh drinking milk 4.5 %, yoghurt 3.6 %, white brined cheese, yellow cheese), sets of demand areas for dairy products produced, set of facilities for DWS processed, set of biorefineries that should be built and all transport connections between them. It is known: the location of farms and their capacity; the selling price of milk; the locations of dairies and their capacities; the technologies for production of dairy products; the technologies for use of DWS for biodiesel production; the dairy products and biodiesel demands; the environmental burden associated with milk, dairy products and biodiesel distribution in the regions. The transport routes for the feedstock used, milk and dairy products are defined as for each transport connection the available types of transport, the transport capacity, the distance and the GHG emissions from each type of transport are known. A planning horizon for government regulations including manufacturing, design and carbon tax is considered.

3. General formulation of the optimisation problem

The optimization problem is to be determined the optimal operating conditions of considered SC, which includes: Dairy farms portfolios; Dairy plants portfolios; Size, capacity and location of biorefineries that should be built; Optimal performance of biorefineries; Transportation connections.

3.1. Formulation of the SC deterministic model

MILP optimisation model including data sets, decision variables, mathematical models of the environmental and economic performance of the considered SC, constraints and optimization criterion is defined. The optimisation criterion comprises an economic assessment and the environmental impact assessment is determined as a constraint. A set of time intervals is defined on the planning horizon $t = \{0,1,2,\dots,T\}$. The index t indicates the variable or parameter corresponding to the t^{th} planning interval. SC for a long planning horizon is considered H (10 y). The whole planning horizon is divided into several equal time intervals $t = \{0,1,2,\dots,T\}$, each of which has a duration ∇t. Within the planning horizon, it is assumed that the consumption of dairy products will change by an estimated value.

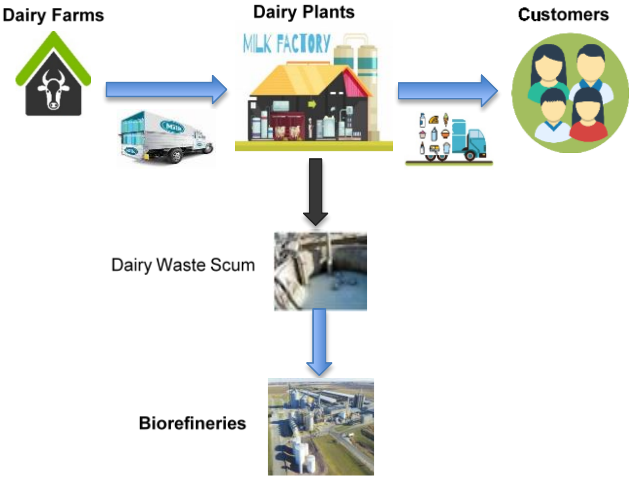

Figure 1: Combined dairy and biodiesel/diesel SC

3.1.1. Decision variables

The following decision variables are defined: SC, which includes: number, size and location of biorefineries; flows of each type of milk; dairy products and DWS between regions; type of transportation for their delivery; GHG emissions for each stage of the life cycle; transportation costs for each transport connection and transportation mode.

3.1.2. Modeling the environmental performance of combined dairy and biodiesel/diesel SC

The environmental impact of the combined dairy and biodiesel/diesel SC is measured in terms of total GHG emissions $(kgCO_{2eq})$, generated across the all SC activities. They are converted into carbon credits multiplied by the price of carbon emissions on the market $(kgCO_{2eq})$.
The aim is to minimize the total amount of equivalent GHG emissions resulting from the operation of the combined dairy and biodiesel/diesel SC. The determination of this objective function is based on a life cycle analysis, which includes:

- GHG emissions released during the production of the dairy products in the dairy plants;
- GHG emissions from the transport of raw materials, dairy products and DWS to biodiesel production facilities;
- GHG from the use of unused DWS for biodiesel production;
- GHG emissions from biodiesel production using DWS as feedstock.

The environmental assessment criteria represent the overall environmental impact of the operation of the combined dairy and biodiesel/diesel SC, through the resulting GHG emissions for each time interval $t \in T$. These GHG emissions are equal to the sum of the environmental impacts of each stage of the life cycle. GHG emissions are usually determined as follows for each time interval $t \in T$.

$$EIJ_t = EPI_t + EPB_t + EWS_t + ETF_t\,, \quad \forall t \tag{1}$$

where,
EIJ_t - total environmental impact of the operation of the combined dairy and biodiesel/diesel SC for the whole life cycle, $[kgCO_{2eq}/d]$;
EPI_t - environmental impact in the production of dairy products in dairy plants, $[kgCO_{2eq}/d]$;
EPB_t - emissions from biodiesel production using DWS as feedstock, $[kgCO_{2eq}/d]$;
EWS_t - emissions from unused DWS for biodiesel production, $[kgCO_{2eq}/d]$;
ETF_t - emissions released during transport of raw materials, products and DWS to the respective facilities, $[kgCO_{2eq}/d]$.

• **GHG emissions per day EPI_t in the production of the dairy products in the dairy plants,** $[kgCO_{2eq}/d]$.

GHG emissions generated from the production of the dairy products depend on the of the technologies used and the regions in which the dairy plants are located. Production of the dairy products can be defined as follows:

$$EPI_t = \sum_{i\in I} \sum_{m\in M} \sum_{k\in K} (EIM_{it}CI_{imkt}PIB_{imkt}), \quad \forall t \tag{2}$$

Where EPI_t is the total environmental impact generated from the production of the dairy products in all regions per day $[kgCO_{2eq}/d]$.

• **GHG emissions per day EPB_t in the production of biodiesel from dairy waste scum,** $[kgCO_{2eq}/d]$.

The environmental impact of the biodiesel production depends on the feedstock and the technology for biodiesel production used. The GHG emissions are generated in a proportion to the amount of feedstock used.

$$EPB_t = \sum_{j\in J} \sum_{f\in F} \sum_{p\in P} \left(EFB_{jfp}PBFP_{jfpt}\right), \quad \forall t \tag{3}$$

Where EPB_t is the total environmental impact of the biodiesel production, $[kgCO_{2eq}/d]$.

Only one biorefinery with size $p \in P$ can be selected for the region $f \in F$ and $PBFP_{jfpt}$ is equal to "0" for all except the selected size of the biorefinery $p \in P$.

• **GHG emissions per day EWS_t generated during the use of unused** DWS **for the biodiesel production,** $[kgCO_{2eq}/d]$.

$$EWS_t = \sum_{j\in J} \left(\sum_{m\in M} \sum_{k\in K} \left(\sum_{i\in I} (\beta_{ijmkt}CIJ_{ijmt}CI_{imkt}PIB_{imkt}) - \sum_{l\in L} \sum_{f\in F} (QJ_{jmft}) \right) \right) EDWS_j, \quad \forall t \tag{4}$$

Where

β_{ijmkt} - production rate of DWS of type $j \in J$ in the production of the $i \in I$ product in the dairy plant $m \in M$ using $k \in K$ type of raw material in the time interval $t \in T$, $[t/t]$;

CIJ_{ijmt} - parameter equal to “1” if the final product generates a DWS of type $j \in J$ from region $m \in M$ for the time interval $t \in T$ and otherwise it is "0 " [t/d];

CI_{imkt} - parameter equal to “1” if the final dairy product can be produced in a dairy plant $m \in M$ using $k \in K$ milk type for the time interval $t \in T$ and otherwise it is "0";

PIB_{imkt} - final dairy product of type $i \in I$ produced in a dairy plant by $m \in M$ using $k \in K$ milk during the time interval $t \in T$, $[t/ d]$;

QJ_{jmflt} - flow rate of DWS of type $j \in J$ provided by vehicles $l \in L$ from the dairy plant $m \in M$ in region $f \in F$ during time interval $t \in T$, $[t/ d]$;

$EDWS_j$ - GHG emissions generated during disposal of DWS type $j \in J$, $\left[\frac{kgCO_2-eq}{solid\ waste}\right]$.

• **Environmental impact of transportation of milk, dairy products and dairy waste scum,** ETF_t $[\boldsymbol{kgCO_{2eq}/d}]$.

The GHG emissions due to transportation depend on the distance, the specific types of vehicles and the amount of delivered raw materials and products. It is determined as follows:

$$ETF_t = ETNM_t + ETMC_t + ETMF_t, \quad \forall t \tag{5}$$

where

ETF_t - total environmental impact of transportation of raw materials, dairy products and DWS for whole life cycle $[kgCO_{2eq}/d]$;

$ETNM_t$ - environmental impact of transportation of raw materials for whole life cycle $[kgCO_{2eq}/d]$;

$ETMC_t$ - environmental impact of transportation of dairy products for whole life cycle $[kgCO_{2eq}/d]$;

$ETMF_t$ - environmental impact of transportation of DWS for whole life cycle $[kgCO_{2eq}/d]$.

3.1.3. Modeling the economic performance of combined dairy and biodiesel/diesel SC

The annual operating costs of the considered SC include: the costs for production of raw materials (milk), the costs for the production of dairy products, the costs for the biodiesel production from DWS and the costs for transportation of raw materials and products. Production costs include: fixed annual operating costs, as a percentage of total investment capital, and variable costs, which are proportional to the processing amounts. Transport costs take into account both loading and unloading activities (fixed costs) which don’t depend on the distance and the price of the fuel, driving and maintenance costs (variable costs) which depend on the distance. The economic assessment determines depending on the total investment costs for the biodiesel production

facilities, costs for building the biodiesel production facilities and the operation of the combined dairy and biodiesel/diesel SC for the planned time horizon.
They determine for each time interval $t \in T$ as follows:

$$TDC_t = TIC_t + TPC_t + TDWS_t + TDKN_t + TPI_t + TPW_t + TTC_t + TCO2_t - TB_t - TL_t, \forall t \quad (6)$$

where,
TDC_t - total costs of the combined dairy and biodiesel/diesel SC per year [$\$/y$];
TIC_t - total investment costs for production capacity of the combined dairy and biodiesel/diesel SC compared to the period of operation and the purchase of the biodiesel plant per year, [$\$/y$];
TPC_t - production costs for the total amount of biodiesel, [$\$/y$];
$TDWS_t$ - costs of purchasing DWS for biodiesel production, [$\$/y$];
$TDKN_t$ - costs of purchasing milk for the production of dairy products, [$\$/y$];
TPI_t - costs for the production of dairy products, [$\$/y$];
TPW_t - production costs for use of unused DWS for biodiesel production, [$\$/y$];
TTC_t - total transportation costs for the combined dairy and biodiesel/diesel SC, [$\$/y$];
$TCO2_t$ - carbon tax charged according to the total amount CO_2 generated during the operation of the combined dairy and biodiesel/diesel SC, [$\$/y$];
TB_t - revenue from the sale of biodiesel produced by all built biorefineries, [$\$/y$];
TL_t - government incentives for biodiesel production and building, [$\$/y$];

3.2. Constraints

The constraints providing the feasibility of the obtained optimal SC which are defined as linear functions of the all decision variables are with respect to:

- The capacity of biorefineries, the stream flowrates, the dairy products demands;
- The amounts of milk needed to produce the dairy products;
- Logistical and transport constraints;
- The use of total amounts of generated in the dairy plants DWS for biodiesel production;
- The material balance for the combined dairy and biodiesel/diesel SC;
- The implementation of the annual capacities of the dairy plants;
- The maximum annual farm capacity $n \in N$ for the production of milk of type $k \in K$, [t/y];

3.3. Optimization criterion

The economic optimization criterion is considered. The environmental impact assessment is defined as a constraint. The economic objective is to minimize the total annual costs of the SC, including the total annual capital costs, the annual operating costs, the annual government incentives and the emission costs, [\$]. The optimization problem for determining the optimal location of the facilities in the regions and their parameters is formulated as follows:

$$Find: X_t[Decision\ variables]\ MINIMIZE\{COST(T_t)\}\ s.t.: \{Constraint\ s\} \quad (7)$$

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

where
LT_t - duration of time intervals $t \in T$, [y]. The objective function (7) and all constraints are linear functions of all decision variables.

Table 1: Distribution of GHG emissions

	Time interval 1	Time interval 2	Time interval 3	Time interval 4	Time interval 5
			$[kgCO_{2eq}/d]$		
EPI_t	33,048	33,048	33,048	33,048	33,048
EPB_t	61.24	61.24	61.24	61.24	61.24
EWS_t	76,994	76,994	76,994	76,994	76,994
ETF_t	24.77	19.67	19.61	19.63	15.76
EIJ_t	110,128	110,123	110,123	110,123	110,119

4. Results and discussion

The MILP models were solved using GAMS 31.2.0. The obtained results are listed in Tables 1 and 2. The analysis of the distribution of GHG emissions shows that the total GHG emissions generated by the operation of the SC for all time intervals are mainly due to the production of the products in dairies and in the utilization of unused DWS for production of biodiesel. The obtained total annual cost amounts to 10,593,364 [$].

Table 2: Distribution of SC costs for biodiesel production

	Time interval 1	Time interval 2	Time interval 3	Time interval 4	Time interval 5
			$\$/y$		
TL_t	1,973	1,973	1,973	1,973	1,973
TB_t	11,567	11,567	11,567	11,567	11,567
$TCO2_t$	39,9214	399,196	399,196	399,196	399,182
TTC_t	4,439	3,841	3,828	3,837	3,407
TPW	1,255,338	1,255,338	1,255,338	1,255,338	1,255,338
TPI_t	116,640	116,640	116,640	116,640	116,640
$TDKN_t$	109,350	109,350	109,350	109,350	109,350
$TDWS_t$	70,762	70,762	70,762	70,762	70,762
TPC_t	176,904	176,904	176,904	176,904	176,904
TIC_t	760	0	0	0	0
TDC_t	2,119,867	2,118,491	2,118,478	2,118,486	2,118,042

5. Conclusions

The study proposes an optimization model for strategic design of a combined dairy and biodiesel/diesel SC using DWS as a feedstock generated from dairy SC. The optimization model is formulated in terms of MILP providing economic and environmental assessments of the SC performance. Implementation of the approach on a real case study from Bulgaria gives the optimal values of total annual operating costs of the combined SC as well as values of GHG emissions related to the implementation of its activities. The largest contribution to GHG emissions is made by the production of the products in dairies and the utilization of unused DWS for the production of biodiesel.

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