



Optimisation of farm production based on statistical data and environmental constraints

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► **Abstract.** Limited land, labour, feed, and financial resources determine the production structure of farms, while increasingly stringent sustainability requirements require economic efficiency to be balanced with the rational use of natural resources. The study aimed to substantiate an optimal production programme for a mixed farm using economic and mathematical modelling that accounts for economic, resource, technological, and environmental constraints. The information base was developed using official statistical data for 2024-2025. A mixed-integer linear programming (MILP) model implemented in R was used to optimise the production structure. The model incorporated constraints on land, labour, feed, and financial resources, as well as greenhouse gas emissions, livestock density, soil organic matter balance, and water use. Scenario analysis was applied to assess the effects of additional requirements. Under the baseline scenario, the optimal plan included 32 head of cattle, 1.18 t of poultry, 9.84 ha of berries for wholesale sales, and 10.00 ha for retail sales, generating a contribution margin of UAH 3,001.94 thousand. Environmental constraints reduced the number of cattle to 28 head and increased poultry production to 5.63 t, while berry production areas changed only slightly. The water constraint resulted in a reduction in the area allocated to berry production and a change in the livestock structure. The combined application of environmental and water constraints produced the most substantial structural adaptation and reduced the contribution margin by 16.60% compared with the baseline scenario. The practical significance of the study lies in the possibility of using the model to substantiate farm production programmes and assess their adaptation to changes in resource and environmental conditions

► **Keywords:** mixed farming; economic and mathematical modelling; production optimisation; linear programming; resource efficiency; environmental criteria; sustainable agriculture

► Introduction

The relevance of the study is determined by the need to improve production planning in farms under constraints on land, labour, financial, and other production resources. For mixed-profile farms, this problem is further complicated by the interdependence of individual production activities, as the allocation of land, labour, feed, and working capital to one type of production directly affects the opportunities available for other activities. At the same time, increasingly stringent requirements for the environmental

sustainability of agricultural production necessitate the incorporation of environmental criteria directly into production planning. Under these conditions, economic and mathematical modelling provides a means of formalising the relationships between production activities, resources, and constraints and of determining an appropriate production structure under a given set of conditions.

Recent studies on agricultural production planning have predominantly focused on formalising resource and

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technological relationships using mathematical programming methods. V. Borysenko & D. Borysenko (2024) applied an optimisation approach to production planning and production cost modelling in farms, emphasising the relationship between production structure and the use of resource potential. Their approach confirms the relevance of formalised models for determining economically justified production decisions under resource constraints. O.Yu. Starikov *et al.* (2024) focused on optimising the structure of sown areas in an agricultural enterprise while accounting for technological characteristics of production. This demonstrates that contemporary agricultural optimisation extends beyond a simple comparison of the profitability of individual crops and considers the interdependence of production processes and resource constraints. O. Radzievska & I. Kovalska (2024) further contributed to this line of research by applying mathematical modelling to determine an optimal production plan under specified constraints.

A subsequent development of this research direction involves the direct incorporation of sustainability criteria into optimisation models. M. Benini *et al.* (2025) developed optimisation models and algorithms for crop planning and rotation in the context of sustainable land use, explicitly incorporating sustainability constraints into a multi-period production planning problem. The proposed approach combines an arc-flow Integer Linear Programming model with algorithmic procedures for optimising crop rotations while simultaneously satisfying environmental requirements. This approach reflects a gradual shift from models primarily oriented towards economic outcomes to formulations in which production decisions must simultaneously satisfy resource and environmental requirements.

The integration of environmental criteria into models covering both crop and livestock production is of particular relevance. Y. Gong *et al.* (2025) developed a mixed-integer linear programming model for the joint optimisation of crop and dairy feeding plans while accounting for enteric methane emissions. Their findings demonstrate the potential of MILP to identify trade-offs between production decisions and the environmental impacts of dairy farming. Compared with models focused exclusively on land-use optimisation, this approach provides a higher degree of integration between production and environmental parameters.

Overall, the current state of research indicates a transition from the optimisation of individual production processes and resources towards integrated modelling of sustainable production systems. However, the literature provides limited coverage of approaches in which a single mixed-integer linear programming (MILP) model for a mixed-profile farm simultaneously integrates land, labour, feed, and financial resources with the technological characteristics of dairy farming, poultry production, and berry production, including different product marketing channels. Further attention is also required to parameterising such models using official regional statistical data, thereby ensuring reproducibility and adaptation to specific farming conditions. In addition, the sequential assessment of the effects of different groups of environmental constraints – including greenhouse gas emissions,

livestock density, soil organic matter balance, and water use – on the optimal production structure and economic outcome remains insufficiently addressed.

The aim of the study was to develop a methodologically consistent optimisation model for production planning in a mixed-profile farm that combines an economic optimisation criterion with production, resource, technological, and environmental constraints by transforming official statistical data into parameters of a mixed-integer linear programming problem. To assess the effects of environmental requirements, a scenario-based approach was applied, involving the sequential expansion of the constraint system and evaluation of its effects on the optimal production structure, resource use, and operating result of the farm. The scientific novelty lies in the development of a methodological approach to parameterising a farm production planning optimisation model that systematically integrates official regional statistical data, economic and technological coefficients, and resource norms within a single MILP framework. Unlike approaches focused on the optimisation of individual crops, production processes, or separate environmental indicators, the proposed model integrates economic, resource, technological, and environmental constraints across different farm activities. In addition, a scenario mechanism is proposed for the sequential incorporation of environmental criteria, enabling the quantitative assessment of the trade-off between economic efficiency and the environmental balance of the production programme.

► Materials and methods

The study was conducted in three consecutive stages. At the first stage, an information base was formed based on official statistical data on crop and livestock production, crop yields, land-use structure, feed availability, livestock numbers, average product selling prices, production costs, and other statistical indicators used for parameterising the optimisation model. The information support of the study was based on statistical materials of the State Statistics Service of Ukraine (2025) and the Main Department of Statistics in Kyiv Region (2025) for 2024–2025.

The parameters of the environmental constraints were specified using methodological approaches developed by the Intergovernmental Panel on Climate Change (IPCC), in particular the provisions of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change, 2019), and methodological approaches developed by the Food and Agriculture Organization of the United Nations (FAO), including the Livestock Environmental Assessment and Performance Partnership (LEAP) methodology (Food and Agriculture Organization of the United Nations, n.d.b) and the Global Livestock Environmental Assessment Model (GLEAM) (Food and Agriculture Organization of the United Nations, n.d.a). Data from the AQUASTAT Dissemination System (Food and Agriculture Organization of the United Nations, 2025) were used to assess water use, while the environmental requirements incorporated into production planning were aligned with the approaches of the European Commission (European Commission, 2023). The object of modelling was a mixed-production farm in Kyiv Region, specified as

a model farm whose parameters were derived from official regional statistical data.

At the second stage, the initial data were statistically processed, including the deflation of monetary indicators to the comparable price base of the fourth quarter of 2025 using official price indices (State Statistics Service of Ukraine, 2025), unification of measurement units, temporal aggregation and seasonal adjustment of indicators, as well as transformation of statistical information into the parameters of the optimisation problem. To ensure data comparability, natural and monetary indicators were harmonised, and coefficients of production resource intensity, marginal income, and technological standards were calculated. The selection of parameters was carried out according to the criteria of representativeness, statistical reliability, and feasibility of practical application in production planning.

To determine the optimal production structure of the farm, a MILP model was developed and implemented in R using the lpSolve package. The objective function maximised the farm's operating result, while the decision variables represented production volume across the main activities and the corresponding allocation of output among sales channels. The model included dairy cattle production, poultry production, and berry production, with berry output allocated between wholesale and retail sales channels. The resource constraints of the optimisation model were structured into four main blocks: land, financial, labour, and feed resources. The total farm area was set at 100 ha as a scenario parameter representing the scale of the modelled mixed-production farm. The area effectively available for production was determined after accounting for land occupied by buildings, internal roads, technological access routes, and headlands. Working capital was capped at UAH 5,000,000, which defined the maximum amount of financing available for current production expenditures. Labour availability was specified on a quarterly basis to account for seasonal fluctuations in the supply of labour in the regional agricultural labour market. Its parameterisation was based on official statistical data on the labour force, the number of employees, and hours worked in Kyiv Region (Main Department of Statistics in Kyiv Region, 2025). For the third quarter, characterised by peak seasonal agricultural activity, available labour was set at 25,000 person-hours as an estimate of the potential labour supply that could be mobilised from the regional labour market.

The feed base was aggregated using a single physical measure – tonnes of dry matter – to ensure comparability between the feed requirements of dairy cattle and poultry production. The potential feed supply was determined based on the arable land available after excluding areas allocated to infrastructure and the minimum assumed yield of a forage crop. This approach provided a conservative estimate of the potential dry-matter supply and established an upper bound on feed resources, thereby aligning livestock production requirements with the available land base. A separate group of constraints covered technological and organisational conditions related to production capacities and sales-channel capacity.

To ensure the required production structure, binary variables were introduced to indicate whether a

particular production activity is operated. The structural constraints required at least three production activities to be active and imposed a minimum production scale for each active activity. For berry production, additional constraints accounted for post-harvest handling capacity and sales-channel capacity, including an upper limit on the volume of berries that could be sold through the retail channel. The combined resource, structural, technological, and organisational constraints defined the feasible region of the optimisation problem, within which the optimal production programme of the farm was determined.

The objective function maximised the farm's operating result, defined as the difference between revenues from product sales and variable production costs. This criterion made it possible to assess the economic effect of allocating scarce resources among competing production activities and to determine their optimal combination. At the same time, the sequential introduction of environmental constraints allowed the effect of environmental requirements on the economic performance of the optimal production programme to be assessed. Given the specified economic, resource, technological, structural, organisational, and environmental conditions, the optimisation problem was formulated as a mixed-integer linear programming problem with binary variables. The general form of the mathematical model was as follows:

$$\max Z = \sum_i (r_i - c_i) x_i, \quad (1)$$

where x_i variables represent production volumes by activity types (Dairy, Poultry, Berries) and sales variables (wholesale/retail).

The selection of this objective function made it possible to evaluate the short-term operating result without considering changes in fixed assets and fixed costs.

The constraint system included resource limits:

Land resource constraint:

$$a_{\text{milk}} x_{\text{milk}} + a_{\text{meat}} x_{\text{meat}} + a_{\text{berry, opt}} x_{\text{berry, opt}} + a_{\text{berry, ret}} x_{\text{berry, ret}} \leq A, \quad (2)$$

where A represents the available land area.

Feed constraint:

$$f_{\text{milk}} x_{\text{milk}} + f_{\text{meat}} x_{\text{meat}} \leq F, \quad (3)$$

where F represents the annual feed supply measured in tonnes of dry matter.

Quarterly labour constraints:

$$\sum_i l_{i,q} x_i \leq L_q, \quad q = I, \dots, IV, \quad (4)$$

where L_q represents the available labour resources in each quarter and may become a potential bottleneck in the third quarter.

Working capital budget constraint:

$$\sum_i c_i x_i \leq B, \quad (5)$$

where B represents the maximum allowable volume of variable costs at 2025 prices.

Specific berry production constraints considered processing capacity, cold chain capacity, and minimum/maximum shares of sales channels, for example:

$$x_{\text{berry,ret}} \leq U_{\text{ret}}, \quad (6)$$

where U_{ret} determines the upper limit for the retail sales channel.

The model variables were primarily continuous; however, binary variables were introduced to describe technological thresholds and minimum allowable production scales. These variables ensured activation of the corresponding production activities only when the established production level was reached. This approach allowed the discrete nature of certain managerial decisions related to launching production processes to be taken into account while maintaining the relative simplicity of the mathematical formulation of the mixed-integer programming problem.

At the final stage of the study, a scenario analysis was conducted by sequentially expanding the set of model constraints. The baseline scenario incorporated economic, resource, and technological constraints. The second scenario additionally introduced environmental constraints on total greenhouse gas emissions expressed in CO₂ equivalents, the maximum permissible livestock density per unit of agricultural land, and the minimum permissible soil organic matter balance. In the third scenario,

a constraint on water resource use was introduced while maintaining the baseline model conditions. The fourth scenario examined the combined effect of environmental and water constraints on the structure of the optimal production plan. The parameters of the environmental constraints were derived from the methodological approaches described above and adapted to the conditions of the modelled farm. The sequential scenario design made it possible to quantitatively assess the effects of individual groups of environmental constraints on the structure of the optimal production plan, the use of production resources, and the farm's operating result.

► Results and discussion

As a result of the parameterisation, a consistent set of economic, technological, and resource coefficients was developed for the production activities included in the model. Monetary indicators were converted to a comparable price basis for the fourth quarter of 2025, after which revenue, variable costs, and requirements for the main production resources – land, labour, and feed resources – were determined for each activity. The resulting parameters ensure consistency between monetary and physical indicators and were used to construct the resource and technological constraints of the optimisation model. The parameterisation results for the production activities are presented in Table 1.

Table 1. Economic and resource parameters of production activities in the optimisation model (base: Q4 2025)

Indicator	Farm activity			
	Milk, 1 cow-year	Poultry, 1 t live weight	Berries, wholesale, 1 ha-season	Berries, retail, 1 ha-season
Revenue, UAH	148,000	69,000	121,000	168,000
Feed / Fertilisers, UAH	58,000	25,000	19,000	22,000
Energy, UAH	12,000	4,500	7,000	9,000
Veterinary services and veterinary medicines/Crop protection, UAH	8,500	2,500	2,500	3,000
Logistics and post-harvest processing, UAH	9,500	3,500	20,000	32,000
Other variable costs, UAH	15,000	6,500	10,500	10,000
Total variable costs, UAH	103,000	42,000	59,000	76,000
CONTRIBUTION MARGIN, UAH	45,000	27,000	62,000	92,000

Source: authors' calculations based on data from the Main Department of Statistics in Kyiv Region (2025)

The activities included in the model were measured in different units – one cow-year, one tonne of live weight, and one hectare per season – so the coefficients presented in Table 1 were directly comparable only in relative terms. In relative terms, berry production was the most profitable activity: the contribution margin accounted for 51.2% of revenue in the wholesale channel and 54.8% in the retail channel, against 30.4% in dairy farming and 39.1% in poultry production. The cost structures differed as well: in the livestock activities the largest share of variable costs was formed by feed (56.3% in dairy farming and 59.5%

in poultry production), whereas in berry production the dominant item was logistics and post-harvest handling (33.9% and 42.1% of variable costs in the wholesale and retail channels, respectively). Compared with the wholesale channel, retail sales of berries increased revenue by 38.8% and variable costs by 28.8%, resulting in an additional contribution margin of UAH 30 thousand per hectare and increasing the economic attractiveness of the retail channel in the optimal plan. The solution of the optimisation problem obtained through the implementation of the proposed model in the R environment is presented in Table 2.

Table 2. Optimal production plan for the farm under technological and economic constraints

Production activity	Optimal volume	Marginal income per unit, thousand UAH	Contribution to the result, thousand UAH
Dairy farming	32 cows	45	1440.00
Poultry production	1.18 tonne of live weight	27	31.86
Berry production (wholesale channel)	9.84 ha	62	610.08

Table 2, Continued

Production activity	Optimal volume	Marginal income per unit, thousand UAH	Contribution to the result, thousand UAH
Berry production (retail channel)	10.00 ha	92	920.00
Total/Operating Result			3001.94

Source: authors' calculations based on the developed optimisation model and statistical data from the Main Department of Statistics in Kyiv Region (2025)

The optimal production plan determines the most efficient structure of farm activities under a given system of resource, technological, and organisational constraints. At the same time, the practical use of optimisation results requires an assessment of how changes in the operating conditions of the farm affect the production structure, resource use, and economic performance. For this purpose, scenario analysis was applied, in which additional environmental and water requirements were successively added to the baseline system of constraints. This approach makes it possible to assess not only the optimisation outcome under baseline conditions but also the way in which the production structure adapts to additional regulatory requirements. In particular, comparison of the scenarios makes it possible to identify changes in the composition of production activities, the use of key resources, and the contribution margin resulting from individual groups of constraints. At the next stage of the study, the environmental and water requirements used to construct the respective scenarios were formulated.

Approaches under the European Union's Common Agricultural Policy (CAP) 2023-2027 (European Commission, 2023) to enhancing the environmental sustainability of agricultural production emphasise the integration of environmental and climate objectives into agricultural production and farm management through enhanced conditionality, including Good Agricultural and Environmental Conditions (GAEC), and voluntary eco-schemes (European Parliament, Council of the European Union, 2021). In this study, the impact of these criteria on the optimisation outcomes was assessed using four sequential scenarios. The baseline scenario was defined as the search for an optimal solution subject only to economic, resource, and technological constraints and represented a production plan aimed at maximising the operating result. The second scenario extended the baseline model by introducing environmental constraints, including a greenhouse gas emissions threshold of 2.5-3.0 t CO₂-eq./ha, a maximum livestock density of 1.7 livestock units/ha of agricultural land, and a non-negative soil organic matter balance (at least 0 t/ha). These threshold values were specified as scenario parameters based on relevant international methodological approaches and were adapted to the conditions of the modelled farm. This specification made it possible to quantitatively assess the effects of environmental constraints on the production structure and operating result. The third scenario additionally incorporated a constraint on water use, which allowed the effects of further environmental restrictions on the optimal production plan to be assessed. Water use was considered as a separate additional constraint because it represented the use of a local natural resource

whose availability depended on regional climatic and environmental conditions. Unlike greenhouse gas emissions, livestock density, and soil organic matter balance, which were considered key components of the environmental sustainability of agricultural production, the water constraint was treated as an independent factor, whose effect on the optimal production structure was assessed in a separate scenario.

Four scenarios were developed to assess the effects of the additional requirements. The baseline scenario represented farm operation under the basic system of economic, resource, technological, and organisational constraints. The environmental scenario supplemented the baseline system with requirements concerning total greenhouse gas emissions, the maximum permissible livestock density, and the minimum soil organic matter balance. The water scenario retained the baseline conditions and additionally imposed a constraint on water use. The combined scenario incorporated the baseline conditions together with all environmental and water requirements. Comparison of the four scenarios made it possible to assess the effects of individual groups of additional constraints on the structure of the optimal production plan, resource use, and the farm's contribution margin. This approach made it possible to distinguish the effects of environmental and water requirements and to assess their combined impact.

In the combined scenario, environmental and water requirements were imposed simultaneously, making it possible to assess their joint effect on the optimal production structure and the farm's economic performance. Unlike the scenarios in which environmental and water constraints were analysed separately, their simultaneous application required a comprehensive adjustment of the production plan, taking into account the interactions among land, water, and other production resources. Comparison of the combined scenario with the baseline, environmental, and water scenarios made it possible to identify additional changes in the production structure and assess the overall economic effect of simultaneously meeting environmental and water requirements. Comparison of the scenarios made it possible to determine the contribution of individual groups of environmental constraints to changes in the optimal production plan and to quantify the reduction in the operating result associated with stricter environmental requirements. The findings illustrated the trade-off between maximising economic efficiency and ensuring the environmental sustainability of agricultural production in accordance with contemporary principles of sustainable agricultural development. The optimal solutions of the model under four different scenarios are presented in Table 3.

Table 3. Comparison of optimal farm production plans under different constraint scenarios

Scenario	Cattle, head	Poultry, t	Wholesale berries, ha	Retail berries, ha	Marginal income, thousand UAH
Baseline	32.00	1.18	9.84	10.00	3,001.94
Environmental	28.00	5.63	9.90	9.95	2,941.21
Water	31.00	3.76	6.00	9.50	2,742.52
Environmental + Water	28.00	4.47	5.50	8.50	2,503.69

Source: authors' calculations based on the developed optimisation model, statistical data from the Main Department of Statistics in Kyiv Region (2025), and international methodological guidelines and databases for the environmental assessment of agricultural production, including the IPCC guidelines (Intergovernmental Panel on Climate Change, 2019), FAO LEAP guidelines (Food and Agriculture Organization of the United Nations, n.d.b), GLEAM (Food and Agriculture Organization of the United Nations, n.d.a), and the AQUASTAT Dissemination System (Food and Agriculture Organization of the United Nations, 2025)

The results of the optimisation modelling indicate that the production structure of the farm responds differently to the introduction of environmental and water constraints. Under the baseline scenario, the optimal production plan involves keeping 32 head of cattle, producing 1.18 t of poultry, and cultivating berries on 9.84 ha for wholesale sales and 10.00 ha for retail sales. This production structure generates a maximum contribution margin of UAH 3,001.94 thousand under the specified resource, technological, and economic parameters of the model. The introduction of the environmental constraint leads to a structural adjustment of the production plan. The number of cattle decreases from 32 to 28 head, while poultry production increases from 1.18 to 5.63 t. This change reflects the differentiated contribution of livestock production types to greenhouse gas emissions and indicates a partial substitution of the more environmentally intensive production activity. At the same time, the areas allocated to berry production remain almost unchanged: the area for wholesale production increases to 9.90 ha, while the area for retail production decreases slightly to 9.95 ha. Thus, under the environmental scenario, the main adaptation mechanism is a change in the ratio between livestock production activities rather than a reduction in berry production. The contribution margin decreases to UAH 2,941.21 thousand, representing a 2.02% decline compared with the baseline scenario.

The water constraint produces a different pattern of structural adaptation. The number of cattle decreases only to 31 head, while poultry production increases to 3.76 t. In contrast, the area allocated to berries for wholesale sales decreases from 9.84 to 6.00 ha, while the area for retail production decreases from 10.00 to 9.50 ha. Thus, under water resource scarcity, the model primarily adjusts the areas allocated to the respective crop production activities, indicating a greater sensitivity of the land-use structure to the water constraint. The contribution margin in this case amounts to UAH 2,742.52 thousand, which is 8.64% below the baseline level.

The most substantial transformation of the production structure occurs when the environmental and water constraints are applied simultaneously. The number of cattle decreases to 28 head, poultry production amounts to 4.47 t, the area allocated to wholesale berry production decreases to 5.50 ha, and the area for retail production decreases to 8.50 ha. Thus, the combined constraints result in simultaneous adaptation of both the livestock and crop production components of the farm. Compared with the

baseline scenario, the contribution margin decreases to UAH 2,503.69 thousand, representing a 16.60% decline.

The results demonstrate that environmental and water constraints affect the farm's production structure through different channels. The environmental constraint primarily changes the ratio between livestock production activities, whereas the water constraint has a stronger effect on the land-use structure. When applied simultaneously, these constraints produce the most conservative production plan, in which the reduction of environmental and resource pressures is achieved at the expense of economic performance. This confirms the usefulness of optimisation modelling for identifying combinations of production activities that provide the maximum attainable contribution margin under specified environmental and resource constraints.

The obtained results demonstrated that environmental constraints did not change the overall specialisation of the farm but adjusted the proportions between individual production activities. Compared with the baseline scenario, the environmental constraints primarily led to adjustments in the livestock component of production, while the structure of berry production remained virtually unchanged. The most significant impact was caused by the water-use constraint, which stimulated the redistribution of resources among production activities and eliminated the wholesale berry sales channel, as it had a lower economic return under the tighter resource constraint. At the same time, even under the most restrictive scenario, the model preserved a diversified production structure and generated a positive operating result, which demonstrated the possibility of combining economic efficiency with environmental sustainability requirements in farm production. Overall, the results indicated that the integration of constraints related to greenhouse gas emissions, livestock density, soil organic matter balance, and water use did not contradict the achievement of economic efficiency. Instead, it contributed to the formation of a balanced production structure that ensured rational utilisation of natural resources and complied with sustainable development principles.

The obtained results showed that incorporating environmental constraints into the planning of a small diversified farm affects not only the operating result but also the mechanism of allocating limited resources among activities. The sequential introduction of environmental constraints made it possible to trace how changes in the feasible region of the model transformed the production

structure, resource use, and economic outcomes while keeping the optimisation criterion unchanged. This approach extended the traditional application of linear programming to the optimisation of production resource use in agriculture. G.C. Lomte & S.R. Dhavale (2022) considered optimisation methods as a tool for the rational allocation of agricultural resources, whereas S.A. Nuzhna & N.M. Samarets (2018) focused on optimising the use of production resources by agricultural enterprises. E. De Keyser *et al.* (2024) demonstrated the potential of farm-level linear programming to integrate economic costs with environmental externalities in fertiliser management. In the proposed model, these approaches were extended by incorporating quantitative environmental constraints on greenhouse gas emissions, livestock density, soil organic matter balance, and, in a separate scenario, water use. This made it possible to assess not only the optimal allocation of resources but also the economic and structural consequences of progressively tightening environmental requirements.

An important result concerned the different economic effects of the various groups of constraints. R. Skrynkovskyy *et al.* (2022) proposed an economic-mathematical model for maximising the economic result of an enterprise within the framework of sustainable development. In our study, the economic criterion remained unchanged across all scenarios, while the constraint system was modified. Under this approach, the reduction in the operating result directly reflected the effect of additional environmental requirements on feasible production decisions. The simultaneous introduction of constraints on greenhouse gas emissions, livestock density, and soil organic matter balance reduced the operating result by only 1.6% compared with the baseline scenario. In contrast, the additional water-use constraint reduced the operating result by 9.1% relative to the baseline. Thus, the economic effect of environmental constraints depends not only on their number but also on the criticality of the respective resource for a particular production system. This result complemented the considerations of resource potential and rational farm size addressed by V. Zhmudenko & R. Lishchuk (2021) and A. Hutorov & O. Hutorova (2024). In the proposed model, the farm's resource potential was determined not only by available land, labour, feed resources, and working capital but also by permissible levels of environmental pressure. Consequently, the introduction of environmental constraints effectively changed the economic value of available resources and the relative attractiveness of individual activities. With the economic optimisation criterion unchanged, this was reflected in changes in the optimal production structure.

The change in production structure also demonstrated the adaptive role of diversification. C.A. Reyna-Ramírez *et al.* (2025) demonstrated the importance of mixed crop-livestock systems for improving resource-use efficiency in smallholder farms, while Y. Vittis *et al.* (2021) linked the optimisation of production parameters with improved resource-use efficiency in farming systems. In our study, the diversified structure was maintained across all scenarios, although the relative scale of individual activities changed in response to the new resource constraints. This indicated that diversification was not an explicit

objective of the model but emerged as a result of the optimal reallocation of resources among available activities. Thus, the diversified production structure functioned as an adaptation mechanism to changing resource conditions. A similar relationship between economic and environmental objectives was identified by C.H. Geissler *et al.* (2025), who emphasised the existence of trade-offs between economic outcomes and environmental constraints in agricultural systems. The obtained results refined this conclusion quantitatively: the first group of environmental constraints caused only a minor reduction in the operating result, whereas the water constraint produced a substantially stronger economic and structural effect. Therefore, the magnitude of the trade-off depends on the scarcity and criticality of the constrained resource. The inclusion of soil organic matter balance was also consistent with the growing integration of soil-quality indicators into production-planning models. M.C. Kik *et al.* (2024) showed that incorporating sustainable soil-management indicators can alter optimal production decisions and the economic value of alternative resource-use strategies. In our model, soil organic matter balance was considered jointly with constraints on greenhouse gas emissions and livestock density. Its effect therefore emerged not in isolation but through the combined changes in production structure and interactions between crop and livestock activities.

The most pronounced structural changes were associated with the water-use constraint. Studies by F.J. López-Flores *et al.* (2025) and S. Ababneh *et al.* (2026) highlighted the importance of water as a resource that simultaneously affects the economic performance and environmental characteristics of agricultural production. In our model, tightening the water constraint resulted in the reallocation of resources towards activities with higher economic returns per unit of the scarce resource. In particular, the area allocated to berry production for the wholesale channel was substantially reduced, while the retail channel was retained at a larger scale. Thus, under a tighter resource constraint, the model did not simply reduce total production but altered its structure according to the economic return generated by the use of the constrained resource.

The allocation of berry production between wholesale and retail channels represented another important aspect of the obtained results. A. Javanmardan *et al.* (2024) demonstrated the importance of simultaneously considering multi-product and multi-market dimensions in optimisation models for fruit supply chains. In our model, the allocation of berries between sales channels was also incorporated directly into the optimisation system. Therefore, the distinction between wholesale and retail production was not merely a marketing characteristic but determined different economic returns to land and other limited resources. This helps explain why, under the tighter water constraint, the model reduced the area allocated to wholesale berry production while retaining the retail activity. The obtained results were also consistent with studies in which optimisation is considered at the whole-farm level. D.A. Zuniga Vazquez *et al.* (2021) and A. Muleke *et al.* (2022) demonstrated the relevance of integrated production planning under resource and climate constraints. Unlike these approaches, our study focused on the sequential introduction of environmental constraints

and on tracking not only changes in economic outcomes but also the structural response of the farm. This made it possible to identify which constraints generated the most substantial reallocation of resources.

From a methodological perspective, the results confirmed the relevance of mathematical programming for the integrated analysis of economic and environmental constraints. C. Moulogianni (2022) compared different mathematical programming approaches for sustainable land and farm management, whereas A.G. Rosa *et al.* (2025) considered linear reformulation as a means of improving the efficiency of sustainable farm-operation models. An advantage of the proposed formulation was its ability to modify the constraint system sequentially while keeping the economic criterion unchanged and directly tracing the response of the optimal production structure. This enhanced the interpretability of the results and made it possible to distinguish the effect of changes in the feasible region from the effect of changing the optimisation criterion itself.

Another important finding was the preservation of the farm's mixed production profile across all four scenarios. Even under the most restrictive scenario, the model did not eliminate the livestock activities but changed their relative proportions in combination with berry production. This indicated that production diversification could serve as an adaptation mechanism to resource and environmental constraints: a reduction in one activity could be compensated by an increase in another when the latter provided a more favourable combination of economic return and resource requirements. At the same time, the results needed to be interpreted in light of the model's limitations. The model was static and determined the optimal plan for a single production period under fixed assumptions regarding prices, yields, productivity, and resource availability. Therefore, the resulting structure should not be interpreted as a universal production configuration applicable to all farms. Its practical value primarily consisted in assessing the direction of changes in the optimal solution when the constraint system was modified and quantifying the corresponding economic implications.

The use of official statistical data for model parameterisation was also important. Compared with models based exclusively on expert assessments, this approach provided greater reproducibility of the initial parameters and allowed the model to be adapted to a specific regional environment. However, the aggregated nature of statistical information limited the extent to which the technological characteristics of an individual farm could be captured. Therefore, practical application of the model required further adjustment of individual coefficients according to the actual production technology, land structure, labour availability, and local market conditions. Overall, the sequential introduction of constraints demonstrated that their economic and structural effects depended on the scarcity and importance of the respective resources. The water-use constraint produced the most substantial adjustment of the production structure, whereas the basic set of environmental constraints resulted in only a minor reduction in the operating result. These findings support the use of the proposed approach as a decision-support tool for assessing the economic and

environmental implications of alternative production plans in small diversified farms.

► Conclusions

The study developed a methodologically grounded mixed-integer linear programming model for production planning in a mixed farm. The model transforms official statistical data into the parameters of an optimisation problem and integrates economic, resource, technological, and environmental constraints within a unified decision-support framework. The use of official statistical information as the empirical basis of the model improves its reproducibility, adaptability to farm operating conditions, and practical applicability, while reducing the need for extensive primary data collection. The results confirm that an economically justified production structure can be established under limited land, labour, financial, and material resources.

The scenario analysis demonstrated that different groups of environmental and resource constraints lead to different patterns of adaptation in the production structure. Environmental constraints primarily affect the balance between livestock production activities, while the structure of berry production remains relatively stable under these conditions. In contrast, the water constraint has a more pronounced effect on land-use allocation and the area devoted to berry production. Thus, different constraint groups operate through distinct mechanisms of resource reallocation, supporting the use of separate scenario analysis to assess their effects on farm production planning. The simultaneous application of environmental and water constraints results in the most comprehensive adjustment of the production plan, as it requires the livestock and berry production components to be jointly aligned with the availability of natural and production resources. At the same time, even under the combined constraints, the farm retains a diversified production structure and a positive economic result. This indicates that environmental and water requirements do not eliminate the economic feasibility of production but rather change the optimal configuration of production activities and resource allocation.

Overall, the findings demonstrate that environmental and water constraints do not merely limit the economic potential of the farm; rather, they alter the optimal configuration of its production structure and resource allocation. Optimisation modelling therefore makes it possible not only to identify an economically efficient production plan but also to assess the farm's capacity to adapt to additional environmental and resource requirements. The proposed approach provides a quantitative basis for evaluating the trade-off between economic efficiency, rational use of natural resources, and environmental sustainability and can be applied as a decision-support tool for farm management. Future research should extend the model by incorporating stochastic parameters, multi-period planning, economic risks, and climate scenarios, as well as additional environmental indicators such as biodiversity, carbon balance, soil degradation, and water quality. Such extensions would increase the model's adaptability to changes in the production environment and broaden its practical application in agricultural decision-support systems.

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Оптимізація виробництва фермерського господарства на основі статистичних даних та екологічних обмежень

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► **Анотація.** Обмеженість земельних, трудових, кормових і фінансових ресурсів визначає виробничу структуру фермерських господарств, тоді як посилення вимог до екологічної сталості потребує узгодження економічної ефективності з раціональним використанням природних ресурсів. Метою дослідження було обґрунтування оптимальної виробничої програми фермерського господарства змішаного профілю на основі економіко-математичного моделювання з урахуванням економічних, ресурсних, технологічних та екологічних обмежень. Інформаційну базу сформовано на основі офіційних статистичних даних за 2024-2025 рр. Для оптимізації виробничої структури використано модель змішаного цілочислового лінійного програмування (MILP), реалізовану в середовищі R. Модель включала обмеження щодо земельних, трудових, кормових і фінансових ресурсів, а також викидів парникових газів, щільності поголів'я, балансу органічної речовини ґрунту та водокористування. Для оцінювання впливу додаткових вимог застосовано сценарний аналіз. За базового сценарію оптимальний план передбачав 32 голови велика рогата худоба, 1,18 т птиці, 9,84 га ягід для гуртової та 10,00 га для роздрібною реалізації, а маржинальний дохід становив 3001,94 тис. грн. Екологічні обмеження зменшували поголів'я велика рогата худоба до 28 голів і збільшували виробництво птиці до 5,63 т за незначної зміни площ ягід. Водне обмеження спричиняло скорочення площ ягідного виробництва та зміну структури тваринництва. Комбіноване застосування обмежень зумовлювало найсуттєвішу структурну адаптацію та зниження маржинального доходу на 16,60 % порівняно з базовим сценарієм. Практичне значення дослідження полягає у можливості використання моделі для обґрунтування виробничих програм фермерських господарств та оцінювання їх адаптації до змін ресурсних і екологічних умов

► **Ключові слова:** змішане фермерське господарство; економіко-математичне моделювання; оптимізація виробництва; лінійне програмування; ефективність використання ресурсів; екологічні критерії; стале сільське господарство