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A New Sustainable Multi-objective Agri-food Supply chain in Mushroom Industry

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Abstract *– This study proposes a novel sustainable multi-objective agri-food supply chain in Mushroom industry due to the lack of economic, environmental, and social aspects that the prior studies neglected. The proposed study examines a four-echelon model including suppliers, intermediate manufacturers, final manufacturers and markets (plus secondary market). The model is also validated to provide insights into a relevant industry. The results indicated that investment in the oyster mushroom would lead to economic and social improvements. Moreover, investing in the button mushroom was observed to improve all three sustainability aspects. In the case of investing in the oyster and button mushroom, increasing the capacity of compost factories and sales price would lead to different results. Furthermore, the profitability of the supply chain was found to rise when waste is sold in the secondary market. Therefore, managers can adopt different strategies under different circumstances based on their priorities to raise supply chain profitability.*

Keywords*– Green supply chain, linear programming, Multi-objective programming, Sustainable agri-food supply chain, Uncertain product demand and yield*

I. INTRODUCTION

Today, environmental and social have gained increasing importance in supply chains in both industrial contexts and academic sciences (Nematollahi and Tajbakhsh, 2020). In this paper, we argue that multi-functionality is a value, which extends its benefits along the entire agri-food chain. We present a methodology to aggregate indicators into an evaluation framework, in order to assess the level of multi-functionality along the entire food value chain. We have called this the “extended value” of multi-functionality, since our approach is able to consider not only the farm level, but also extends to the entire food chain. A sustainable supply chain is aimed at managing the supply chain, budget, information, and resources to simultaneously maximize supply chain profitability and social contributions and minimize environmental impact (Hassini et al., 2012).

Farming has long played a major role in human life and continues to be essential under human advances. Soil cultivation accounts for a major portion of human food. Farming also poses a substantial impact on the environment as it is the second-largest producer of greenhouse gasses (GHGs) (IPCC. 2014).

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Banasik et al. (2019) emphasized that the consideration of product demand and yield uncertainty would lead to a more realistic model. However, many important aspects of a supply chain, such as multiple products, different raw materials, multiple echelons, the second market, and social aspects, were neglected for simplification purposes. Thus, the present paper seeks to complete previous models and develop a more efficient agri-food supply chain model.

The main objective and novelty of this paper lie in a four-echelon supply chain with uncertain product demand and yield. This study proposes a multi-product multi-period multi-raw material mathematical model. All three pillars of sustainability (i.e., social, environmental, and economic) are also incorporated into the model. The consideration of the second market helps obtain a more realistic mathematical model. The second market would purchase waste and low-quality products. The proposed model suits products with the same cultivation period; that is, the products that have the same plantation and harvesting schedule. The present work aims to find answers to the following questions:

(1) How are social, environmental, and economic aspects related in an agri-food supply chain?

(2) The improvement of which supply chain parameter (i.e., demand, yield, production capacity, and price) would maximize the value? How does such improvement affect each product?

(3) In the case of multiple products, the selection of what products would improve the economic, environmental, and social performances? What are the short- and long-term outcomes of such selection?

The remainder of the paper is organized as follows: Section 2 reviews the sustainable agri-food supply chain literature; Section 3 states the problem and introduces the four-echelon mathematical model with the parameters and constraints; Section 4 implements the model on the dataset of a real-life mushroom supply chain to evaluate its performance (model approaches); Section 5 decides product selection; and, Section 6 concludes the paper and makes future researcher suggestions.

II. LITERATURE REVIEW

In an investigation, Fogioli et al. (2017) argued that multi-functionality is a value, which extends its benefits along the entire agri-food chain. They presented a methodology to aggregate indicators into an evaluation framework, in order to assess the level of multi-functionality along the entire food value chain, entitled the “extended value” of multi-functionality, since this approach was able to consider not only the farm level, but also extends to the entire food chain.

Federica et al. (2018) stated that integrating the environmental and social sustainability pillars into the lean and agile supply chain is essential. They suggested to develop conceptual and empirical studies on whether and how integration between paradigms is contingent upon the strategic relevance of sustainability.

Nematollahi and Tajbakhsh (2020) conducted a review work and suggested that social aspects had been less often considered compared to environmental aspects in sustainable agri-food supply chains. Moreno-Camacho et al. (2019) reviewed 113 sustainability papers and argued that agriculture was a major field for future research.

Banasik et al. (2017) explored the effects of a closed-loop mushroom supply chain on economic and environmental performance. They studied a single-product multi-raw material supply chain model. However, they did not incorporate product demand and yield uncertainties into their model.

Keyvanshokooh et al. (2016) proposed a novel profit maximization model for Closed-loop Supply Chain Network design as a mixed-integer linear program in which there is flexibility in covering the proportions of demand satisfied and returns collected based on the firm's policies. The major contribution was to develop a novel hybrid robust-stochastic programming approach to simultaneously model two different types of uncertainties by including stochastic scenarios for transportation costs and polyhedral uncertainty sets for demands and returns. In this case, Löhndorf (2016) presented an empirical analysis of popular scenario generation methods for stochastic optimization, including quasi-Monte Carlo, moment matching, and methods based on probability metrics, as well as a new method referred to as Voronoi cell sampling. Solution quality is assessed by measuring the error that arises from using scenarios to solve a multi-dimensional newsvendor problem, for which analytical solutions are available.

Banasik et al. (2019) focused on economic and environmental aspects in a green supply chain and evaluated the contributions of product demand and yield uncertainties. They simplified the problem to improve model performance by incorporating product demand and yield uncertainties; that is, the single-product model had two echelons (i.e., a small-scale compost producer and a mushroom producer) and neglected the social aspect. Furthermore, compost waste after cultivation and sales was not considered.

Bodaghi et al. (2018) investigated the economical conditions of applying a special algorithm by developing a mathematical single-period flexibility measure to extend in a multi-period model for applying in the multi-period supply collaborations.

Yadav et al. (2021) designed a sustainable new food distribution network that takes into account all three sustainability factors. The model presented in this research is a linear programming model that is solved using the Epsilon constraint. In order to test the model, sensitivity analysis was used with data from a tomato supply chain in India. The difference between this article and the present study is that it does not take into account the uncertainties in the demand and harvest parameters. In order to simplify, they considered the proposed model as a single product and the secondary market is not considered in this article.

In some studies, authors analyzed multi-echelon sustainable supply chain with inventory control, routing, and location, Biuki et al. (2020), Zheng et al. (2019), Zahiri et al. (2018). They prioritized the suppliers to improve their proposed model. However, uncertainty was considered neither for product demand nor product yield. Also, waste sales and sales price were neglected.

In another study, authors examined a fresh-food supply chain system with multiple farmers, a single processor, multi-distributor, customers, and multiple periods. This paper presented a mixed-integer linear programming to optimize total purchasing, inspection, food waste, packing, cold storage, transportation, and carbon emission costs by optimizing product inventories and deliveries. The model is also validated to provide insights into relevant industries (Ivan and Iwan, 2022).

Gholami-Zanjani et al. (2021) have designed a multi-objective green three-level supply chain model to meet the needs of meat supply planning and inventory control, which solved the model using stochastic programming. In this paper, by maximizing the supply chain profit and minimizing the emission of pollutants, economic and environmental issues were considered. Uncertainty in environmental issues is one of the most important innovations of this research. But in this study, the relationship between supply chain and social issues of supply chain is ignored. Recently, others have also investigated uncertainty, supply chain and real cases simultaneously, such as Kaviyani-Charati (2022), Schmidt and Moreno (2022), Foroozesh et al. (2022).

Masoudipour et al. (2017) focused on a closed-loop supply chain that allowed for product return. They conducted a case study of the textile industry with three quality levels of returned products. The secondary market was an important component of their model. The returned products with insufficient quality would be sold to the secondary market in the tri-echelon supply chain. Kamal et al. (2022) in a new paper worked on product return in circular economy and Assid et al. (2021) investigated quality-based categorization of returns. In the following, Gholizadeh et al. (2021) focused on supply chain for the dairy industry with robust and heuristic optimization and Ponte et al. (2021) studied quality grading of returns and the dynamics of remanufacturing. However, the effects of environmental and social aspects on the supply chain and product demand and yield uncertainties were neglected.

Jonkman et al. (2019) studied a green supply chain of product cultivation. They designed a model to maximize the profitability of the sugar beet supply chain in the Netherlands. The model consisted of two main objective functions. The first objective function maximized the farmer profit and processing factory profit, while the second one minimized environmental pollution (i.e., CO_2 emission). The present study improves the model of Younkmann et al. (2019) to a more realistic level by incorporating uncertainty, the second market, and social impacts into the model.

Fikry et al. (2021) presented an integrated strategic-tactical planning model for the sugar beet supply chain problem. The proposed model is a linear planning (LP) model that supports important supply chain decisions at three levels of cultivation, transfer and processing. The most important innovation of this research is providing a decision support tool. In order to test the model, a case study in the sugar industry has been used. But in this article, environmental and social issues are not considered. Although researchers have continued this subject (Perdana et al. (2022), Ptak et al. (2021), Ranjbari et al. (2022)), but secondary markets and uncertainty are also not considered in Mushroom industry.

Akbarian-Saravi et al. (2020) introduced a sustainable supply chain model with economic, environmental, and social factors for the production and supply of bioethanol. The model had three objective functions to maximize the social factor (i.e., employment) and minimize costs and environmental impacts (i.e., GHG emission). Product yield and secondary market were lacking in their model. Others also worked on sustainable supply chain model with economic and environmental aspects, for more information see Aba et al. (2020), Ünyay et al. (2022) and Suckling et al. (2021). They suggested that future works include demand and yield uncertainties.

Rohmer et al. (2019) studied sustainable supply chains in the Netherlands. They introduced a two-objective model that was linearly optimized using the meat and dairy supply chain in terms of economic, environmental, and social impacts. The environmental factors included climate, water consumption, land use, and fossil fuel consumption. They incorporated nutrition health as a social factor into the objective functions. They treated the model to be a single-product single-period supply chain for simplification. Some authors recently have studied this context, such as Krishnan et al. (202) and Manteghi et al. (2021). However, it was suggested that future works consider uncertain product demand and yield in various real case studies.

Table I. Remarkable features of this study in comparison with the literature

Study	*Objective Functions*			*Demand*		*Yield*		*Raw Material*		*Product*		*Period*		*Second Market*	*Case Study*	*Closed-loop*
	EC	*EN*	*SO*	*U*	*C*	*U*	*C*	*S*	*M*	*S*	*M*	*S*	*M*			
E. Masoudipour et. al (2017)	■				■					■		■		■	■	■
Banasik et. al (2017)	■	■			■		■		■	■			■		■	■
Rohmer et. al (2018)	■	■	■		■		■		■	■		■			■	
Jonkman et. al (2018)	■	■			■		■		■	■		■			■	
Akbarian-Saravi et. al (2019)	■	■	■	■			■		■	■			■		■	
Banasik et. al (2019)	■	■		■		■		■		■			■		■	
Biuki. et. al (2020)	■	■	■	■					■		■		■			
This Research	■	■	■	■		■			■		■		■	■	■	

Abbreviations: EC: Economic, EN: Environment, SO: Social, U: Uncertainty, C: Certain, S: Single, M: Multi

A review of the literature suggests a lack of an efficient mathematical model to handle important aspects of an agri-food supply chain, such as environmental and social impacts, product selection, the relationship between the supply chain and secondary markets, and uncertainty in determinants (i.e., product demand and yield). The present study proposes a four-echelon multi-product multi-raw material sustainable agri-food supply chain model for products of the same cultivation period. The mushroom industry has a huge potential and requires the outcomes of cultivating different products. This paper adopts a case study and evaluates the contributions of cultivating two mushroom types to environmental, social, and economic aspects.

III. PROBLEM STATEMENT

This study analyzes a four-echelon supply chain primarily aimed at maximizing profitability and social impacts and minimizing environmental impacts. The proposed model is based on a real-life problem in the Iranian mushroom industry. The selected company cultivates oyster and button mushrooms. The supply chain involves four main echelons, including suppliers (of straw and stubble), intermediate producers (of compost), producers of the final product (mushroom), and the major market. These four echelons are situated within a supply chain, and the production amount is determined at the first three echelons. Waste at each echelon is purchased by other supply chains (i.e., the secondary market) as raw materials. The proposed agri-food supply chain model includes a number of assumptions, including:

(1) Multiple products and multiple raw materials; that is, as many raw materials as needed can be produced compost.

(2) Transportation and its costs are considered in the model. Products are purchased in the major market and in the final producer site. Thus, the costs of transportation from the final producer to the major market are paid by the customer.

(3) Waste in the three first layers is sold to the secondary market, including agricultural and husbandry farms.

(4) Uncertainty is included in the model under different scenarios based on product yield and demand distribution functions. Further details are available in Banasik et al. (2019).

(5) The same product cultivation period is assumed.

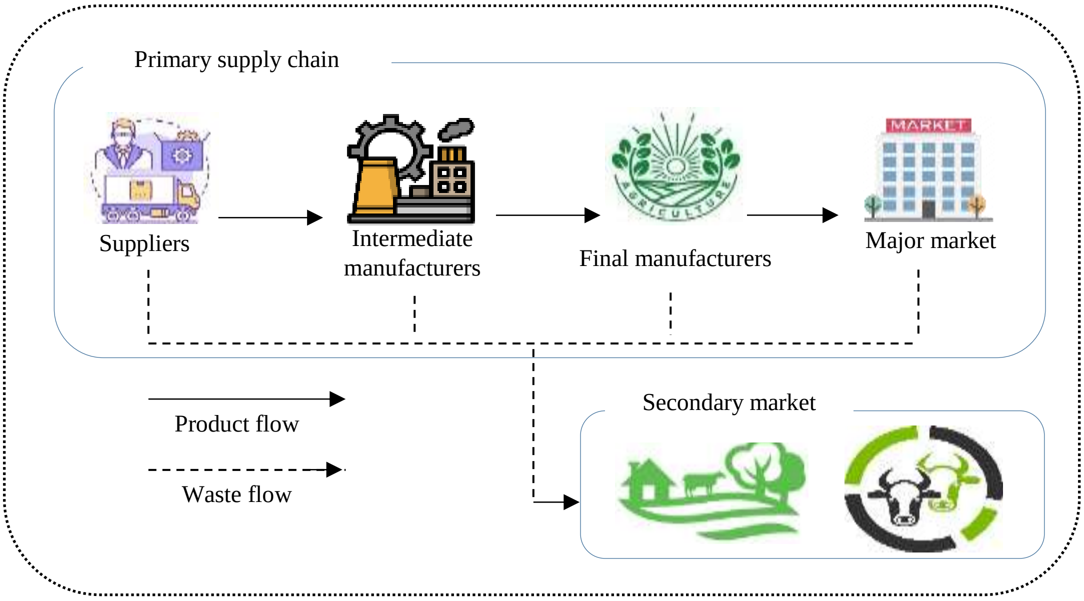

Fig 1. An overview of the proposed SC

A. Mathematical model

The proposed agri-food supply chain is represented by a linear mathematical model. The mathematical model involves three objective functions. Objective function 1 handles the economic aspect. It has three terms. The first term (OF_{eco1}) represents the income of product sales in the supply chain. Since the product yield is related to the number of scenarios, it is required to divide the first term by the number of scenarios (S). Then, high-quality, excess, and low-quality products are multiplied by their corresponding prices. The second term (OF_{eco2}) stands for the sales of waste to the secondary market. The third term (OF_{eco2}) includes the supply chain costs, which are further divided into three sub-costs, namely transportation, variable production, and waste sub-costs. The economic objective function maximizes profitability by summing the two first terms (i.e., the income of product and waste sales) and subtracting the third term (i.e., costs).

Table II. Nomenclature

Sets

C; (c ∈ C)	Size of final products	M; (m ∈ M)	Sets of raw materials
T; (t ∈ T)	Time periods	R; (r ∈ R)	Sets of raw material suppliers
A; (a ∈ A)	Age of intermediate products	I; (i ∈ I)	Sets of intermediate product factories
P; (p ∈ P)	Sets of products	F; (f ∈ F)	Sets of final product factories
J; (j ∈ J)	Sets of intermediate products	S; (s ∈ S)	Sets of scenarios

Parameters

cmm,r	Variable and labor costs of raw material m in supplier r
csj,i	Variable and labor costs of produce intermediate product j in factory i
cpj,f,a	Variable and labor costs of use intermediate product j in f at age a
cmdm,r	Disposal costs of raw material m in supplier r
csdj,i	Disposal costs of produced intermediate product j in intermediate product factory i
cpdj,f,a	Disposal costs of use intermediate product j in f at age a
d_rir,i	Distance between raw material supplier r and intermediate product factory i
d_ifi,f	Distance between intermediate product factory i and final product factory f
ctm	Cost of transportation of raw material m
ctj	Cost of transportation of intermediate product j
ppp,c,t	Selling price of final product p fulfilling demand with size c in period t
psp,c,t	Selling price of final product p exceeding demand with size c in period t
plp,c,t	Selling price of final product p low-quality with size c in period t
srm,t	Selling price of raw material m to the secondary market in time period t
scj,t	Selling price of intermediate product j to secondary market in time period t
sfj,t,a	Selling price of used intermediate product j in time period t at age a to secondary market
e_mum	Environmental impact of production per 1 t of material m
e_wmw	Environmental impact of waste disposal per 1 t of m material
e_om	Environmental impact of transportation material m
e_cuj	Environmental impact of production per 1 t of compost j
e_cwj	Environmental impact of waste disposal per 1 t of spent substrate j
e_nj	Environmental impact of transportation compost j
e_pp	Environmental impact of production per 1 kg of p product mushrooms
e_fwj	Environmental impact of waste disposal per 1 t of spent substrate j
ca_rr,m,t	Capacity of raw material supplier r for raw material m in time period t
ca_ij,i,t	Capacity of intermediate product j produced in factory i in time period t
ca_fcof	Capacity of intermediate product j in factory f
dp,t,s	Demand for final product p in time period t in scenario s
Xj,m	Percentage of ingredients for produce intermediate product j
U	Raw material factory job creation coefficient

V	Intermediate product factory job creation coefficient
W	Final product factory job creation coefficient
drm,r	Fraction of disposed raw material in supplier r
dij,i	Fraction of disposed intermediate product j in factory i
lqp,f,a	Fraction of low-quality final product p in factory f at age a
pdp,j,c,f,t,a,s	Yield of final product p use intermediate product j, size c, factory f, period t, age a, and scenarios
	Decision variables
Om,r,i,t	Amount of raw material m transport between raw material supplier r and intermediate product factory i in time period t
Nj,i,f,t	Amount of intermediate product j transport between intermediate product factory i and final product factory f in time period t
Mp,c,t,s	Amount of premium quality final product p, size c, sold in period t, in scenario s
ODp,c,t,s	Amount of surplus final product p, size c, sold in period t, in scenario s
Lp,c,t,s	Amount of low-quality final product p, size c, sold in period t, in scenario s
mwm,r,t	Amount of material m disposed by raw material supplier r in time period t
mum,r,t	Amount of material m produced by raw material supplier r in time period t
cwj,i,t	Amount of intermediate product j disposed by intermediate product factory i in time period t
cuj,i,t	Amount of intermediate product j produced by intermediate product factory i in time period t
fwj,f,t,a	Amount of intermediate product j disposed by final product factory f in time period t at age a
fuj,f,t,a	Amount of intermediate product j cultivated by final product factory f in time period t at age a

$$MaxZ = OF_{eco1} + OF_{eco2} - OF_{eco3} \tag{1}$$

$$OF_{eco1} = 1/S * \sum_{p,c,t,s} pp_{p,c,t} * M_{p,c,t,s} + \sum_{p,c,t,s} ps_{p,c,t} * OD_{p,c,t,s} + \sum_{p,c,t,s} pl_{p,c,t} * L_{p,c,t,s}$$

$$OF_{eco2} = \sum_{m,r,t} mw_{m,r,t} * sr_{m,t} + \sum_{j,i,t} cw_{j,i,t} * sc_{j,t} + \sum_{j,f,t,a} fw_{j,f,t,a} * sf_{j,a,t}$$

$$OF_{eco3} = \sum_{j,m,r,i,f,t}[(O_{m,r,i,t} * d\_ri_{r,i} * ct_m) + (N_{j,i,f,t} * d\_if_{i,f} * ct_j)] + \sum_{m,r} cm_{m,r} * mu_{m,r} + \sum_{j,i,t} cs_{j,i} * cu_{j,i,t} + \sum_{j,f,t,a} cp_{j,f,a} * fu_{j,f,t,a} + \sum_{m,r,t} cmd_{m,r} * mw_{m,r,t} + \sum_{j,i,t} csd_{j,i} * cw_{j,i,t} + \sum_{j,f,t,a} cpd_{j,f,a} * fw_{j,f,t,a}$$

(2)

$$inOF_{env} = \sum_{m,r,i} e\_mu_m * mu_{m,r,i} + \sum_{m,r,i} e\_mw_m * mw_{m,r,i} + \sum_{m,r,i,t} e\_o_m * O_{m,r,i,t} * d\_ri_{r,i} + \sum_{j,i,t} e\_cu_j * cu_{j,i,t} + \sum_{j,i,t} e\_cw_j * cw_{j,i,t} + \sum_{j,i,f,t} e\_n_j * N_{j,i,f,t} * d\_if_{i,f} + 1/S * \sum_{p,c,f,t,a,s} e\_p_p * pd_{p,j,c,f,t,a,s} * fu_{j,f,t,a} + \sum_{j,f,t,a} e\_fw_j * fw_{j,f,t,a}$$

Objective function 3 maximizes the number of job opportunities created at the first three echelon of the supply chain. To find the number of created job opportunities, coefficients are used to multiply the capacities of the production centers. A larger production capacity would lead to more job opportunities.

$$MaxOF_{soc} = \sum_{m,r,t} mu_{m,r,t} * U + \sum_{j,i,t} cu_{j,i,t} * V + \sum_{j,f,t} fu_{j,f,t,1} * w \tag{3}$$

Eq. (4) is the first constraint of the mathematical model. It ensures that the total input raw material of the intermediate production centers is not larger than their output. Constraint (5) implies that the intermediate product output does not exceed the capacities of the production centers.

$$\sum_{m,r} O_{m,r,i,t} - \sum_{j,f} N_{j,i,f,t} \geq 0 \forall i, \forall t \tag{4}$$

$$\sum_{f} N_{j,i,f,t} \leq ca\_i_{j,i,t} \forall j, \forall i, \forall t \tag{5}$$

Constraint (6) ensures that the amount of the supplied raw materials and waste are not larger than the capacities of the suppliers.

$$mw_{m,r,t} + mu_{m,r,t} \leq ca\_r_{r,m,t} \forall m, \forall r, \forall t \tag{6}$$

Constraint (7) ensures that the amount of the intermediate product and waste does not exceed the capacities of the producers.

$$cw_{j,i,t} + cu_{j,i,t} \leq ca\_i_{j,i,t} \forall j, \forall i, \forall t \tag{7}$$

Constraints (8) and (9) determine the amount of high-quality and excess final products and the amount of low-quality final products, respectively.

$$M_{p,c,t,s} + OD_{p,c,t,s} \leq \sum_{j,f,a}(1 - lq_{p,f,a}) * pd_{p,j,c,f,t,a,s} * fu_{j,f,t,a} \forall p, \forall c, \forall t, \forall s \tag{8}$$

$$L_{p,c,t,s} = \sum_{j,f,a} lq_{p,f,a} * pd_{p,j,c,f,t,a,s} * fu_{j,f,t,a} \forall p, \forall c, \forall t, \forall s \tag{9}$$

Constraint (10) ensures that the demand is supplied by only high-quality final products.

$$\sum_c M_{p,c,t,s} \leq d_{p,t,s} \forall t, \forall s, \forall p \tag{10}$$

Constraint (11) determines that the amount of substrate cultivation (intermediate product) is not larger than the capacity of the cultivation center.

$$\sum_j fu_{j,f,t,a} \leq ca\_fco_f \forall t, \forall f, \forall a \tag{11}$$

Constraints (12) and (13) ensure that the outputs of raw materials and intermediate product do not exceed the output of the production centers.

$$\sum_i O_{m,r,i,t} \leq mu_{m,r,t} \forall t, \forall r, \forall m \tag{12}$$

$$\sum_f N_{j,i,f,t} \leq cu_{j,i,t} \forall t, \forall j, \forall i \tag{13}$$

Constraint (14) implies that the amount of substrate cultivation (intermediate product) is not greater than its input to the production center of the final product on the first day.

$$fu_{j,f,t,a} \leq \sum_i N_{j,i,f,t} \ \forall t, \forall j, \forall f, a = 1 \tag{14}$$

Constraint (15) constrains material combination. The quantities of raw materials and intermediate product are determined by determining the number of raw materials and their optimal combination fractions.

$$\sum_j (cu_{j,i,t} + cw_{j,i,t}) * X_{j,m} = \sum_r O_{m,r,i,t} \ \forall t, \forall m, \forall i \tag{15}$$

Constraints (16) and (17) determine raw material waste and intermediate product waste, respectively.

$$mu_{m,r,t} * dr_{m,r} = mw_{m,r,t} \forall t, \forall m, \forall r \tag{16}$$

$$cu_{j,i,t} * di_{j,i} = cw_{j,i,t} \forall t, \forall j, \forall i \tag{17}$$

Constraint (18) implies that the total substrate cultivation equals the substrate cultivation of the preceding day minus waste.

$$fu_{j,f,t,a} = fu_{j,f,t,a-1} - fw_{j,f,t,a-1} \forall t, \forall j, \forall i \tag{18}$$

Constraint (19) ensures that substrate cultivation is treated as waste on the last day of cultivation.

$$fw_{j,f,t,a} = fu_{j,f,t,a} \forall t, \forall j, \forall f, a = A \tag{19}$$

IV. MODEL APPROACHES

The mathematical model was tested by statistics of a mushroom cultivation company. The tests are divided into four groups: (1) multi-objective optimization, (2) pricing decisions, (3) demand stimulation strategies, and (4) equipment upgrade decisions. To incorporate uncertainty, 10 scenarios of demand and yield are assumed based on their distribution functions.

A. Case study data

The case study company had three straw and stubble farms (suppliers), two compost production centers (intermediate product), and three mushroom cultivation centers (final product). It cultivated oyster and button mushrooms, each with specific compost. Both production centers could produce two types of compost. Since the required space in the mushroom cultivation centers was assumed to be competitive based on Constraint (11), all three mushroom cultivation centers could cultivate the two mushroom types.

The raw materials included straw, stubble, chicken manure, gypsum, ammonium sulfate, molasses, casing soil, water, oyster mushroom spawn, and button mushroom spawn. A virtual supplier was assumed to supply other items than straw and stubble in the model. To produce compost for the oyster mushroom, only water, straw, stubble, and spawn are used.

Straw, stubble, chicken manure, ammonium sulfate, molasses, water, and spawn are also utilized to produce button compost. Casing soil is used to cultivate the button mushroom in the cultivation center, which was considered as a raw material in the model.

To maximize the profit, mushrooms are harvested only in two flushes. This was proved in earlier works (Banasik et al., 2019). The cultivation time of mushrooms was 35 days (10 cultivation periods per year), and the compost production period was 3 and 29 days for the oyster and button mushrooms, respectively

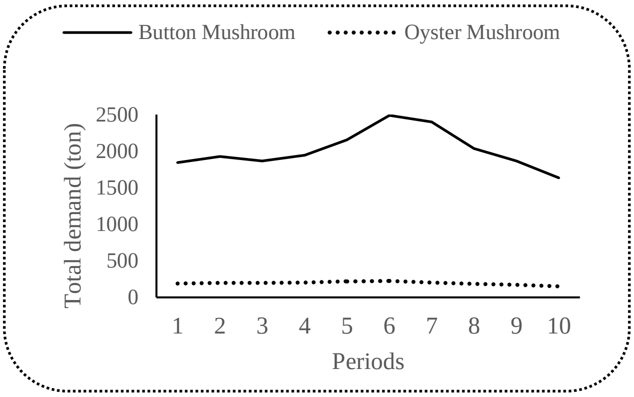

Fig 2. Total demand in time periods

The goodness of fit (GOF) test indicated that the mushroom demand and yield data had a normal distribution. The button mushroom had a mean yield of 174 kg with a standard deviation of 18.64 kg in the first flush and a mean yield of 96.6 kg with a standard deviation of 10.2 kg in the second flush, while the oyster mushroom had a mean yield of 142.8 kg with a standard deviation of 14 kg in the first flush and a mean yield of 53.5 kg with a standard deviation of 8.9 kg in the second flush. Fig. 2 illustrates the demand data. The sales prices are shown in Fig. 3.

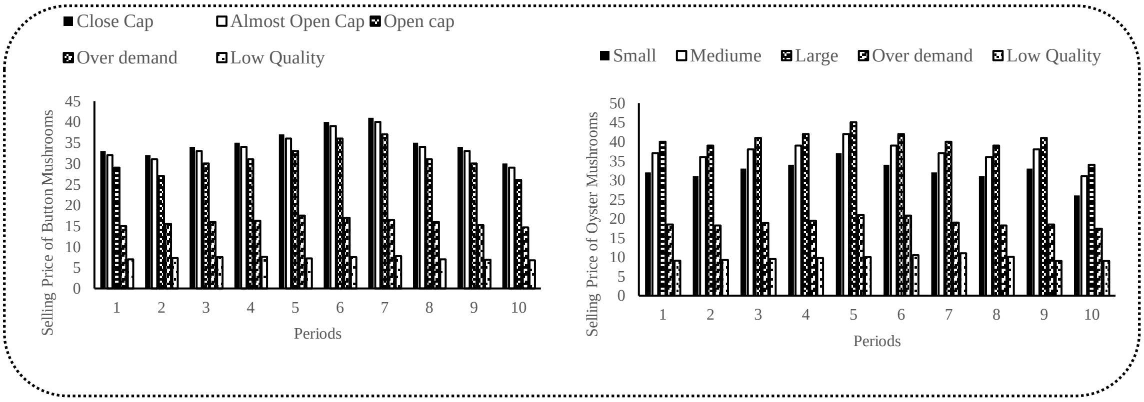

Fig 3. Selling price of oyster and button mushrooms

The total labor and variable production cost (except for that of raw materials) of button mushroom compost in the cultivation center were 70 until day 25 and 80 afterward. Furthermore, the total labor and variable production costs of oyster mushroom compost were 70 until day 27 and 80 afterward. The compost waste cost in the button mushroom center was 10 until day 25 and 12 afterward, while that of the oyster mushroom center was 12 until day 27 and 14 afterward.

The sales price of straw and stubble waste to the secondary market was 200, while the perished composts of button and oyster mushrooms had sales prices of 300 and 200, respectively. Button mushroom compost under cultivation would be sold to the secondary market at a price of 3000 on the first day and 200 on the last day of cultivation. Also, the oyster mushroom compost under cultivation was sold to the secondary market at a price of 1000 on the first day and 30 on the last day of cultivation.

The straw and stubble suppliers had variable capacities over the year. The capacity of supplying straw to the farms was 8400, 6800, and 8700 tons. The same capacities hold for stubble. The model allowed for purchasing straw and stubble at higher prices from the free market in case of profitability. As the mushrooms and button mushroom compost had cultivation periods of 35 and 29 days, respectively, the capacity of compost production centers would be different for different periods during the year. The compost production centers had capacities of 8464 and 7836 tons in periods 5 and 9, respectively, while the capacities would be 4232 and 3918 tons in the other periods. Moreover, the mushroom cultivation centers had capacities of 5536, 6236, and 5223 tons of compost.

Table III. Transportation distances from farms, compost factories and mushroom growers' factories (km)

Farms	***Compost factories***	
	1	2
1	10	8
2	7	8
3	5	10
Mushroom factories		
1	4	5
2	4	5
3	2	5

Table III reports the inter-farm distances, compost production centers, and mushroom cultivation centers. A transportation cost of 10 per ton was assumed.

According to the experts and managers of the mushroom industry, it was found that one job opportunity would be created for 500, 1000, and 200 tons of output in the farms, mushroom cultivation centers, and mushroom production centers, respectively. Since only two raw materials (i.e., straw and stubble) and three initial farms (three straw and stubble supply farms) could create job opportunities in the proposed supply chain, the number of raw materials *m* and the number of farms *r* were assumed to be 2 and 3, respectively.

The input exergy was set based on earlier works (Zisopoulos et al., 2016). The exergy loss of button mushroom production, waste, and transportation was 18 MJ/ton, while that of the oyster mushroom was 26 MJ/ton. Furthermore, the exergy loss of production, waste, and transportation was 2554 and 1901 MJ/ton for button and oyster mushrooms, respectively. Moreover, the exergy loss of production, waste ("champost" waste), and transportation ("champost" transportation) of the spent mushroom substrate was 168 and 239 MJ for the button and oyster mushrooms, respectively. It should be noted that compost would not be steamed ("cooked-out"), and its exergy effects were neglected.

Waste is negligible in compost production centers and farms. However, it is almost high in mushroom cultivation centers. The first and second mushroom cultivation centers produce 7% low-quality mushroom until day 27, which increases to 18% afterward. In light of more efficient and upgraded equipment, the low-quality mushroom fraction is 6% until day 27 and 13% afterward. However, the low-quality oyster mushroom fraction is 1% until day 27 in all three cultivation centers. This fraction rises to 7% in the first and second centers and 6% in the third one.

The present study adopted the epsilon-constraint method to solve the multi-objective model. Further details on the epsilon-constraint methodology are available in Ehrgott (2005). The model was solved using IBM CPLEX Studio on a PC with an Intel Core-i3-3210 3.2 GHz processor and 4GB RAM under Microsoft Windows.

B. Multi-objective optimization

A number of Pareto solutions are provided to improve supply chain decision-makers' knowledge of the relationships between economic, environmental, and social factors. The problem was solved using the data discussed in Subsection 4.1. The maximum profit and exergy release were calculated to be 178.94×10^6, 1.74×10^9 MJ, respectively, with 539 job opportunities created when the economic factor was in priority. In this case, the optimal compost cultivation was found to be 83378 tons, including 76043.74 tons of oyster mushroom compost and 7335.25 tons of button mushroom compost. Table IV reports the Pareto solutions. Supply chain decision-makers need to realize how environmental and social factors influence the profitability of the supply chain. The economic and social objective function values at different exergy losses are reported in Table IV. As can be seen, a reduction in the exergy loss reduced the profitability and number of jobs. Indeed, the production reduced as the exergy loss declined, diminishing profitability and jobs. It should be noted that the environmental impacts could be reduced by 10% for only a 1.9% decline in profitability; however, the number of job opportunities would undergo a significant reduction of 9.74%. The same case holds for the rise of created jobs in number. A maximum of 728 job opportunities was found to be 728, suggesting a 37.68% rise compared to the optimal solution. An increase in the number of job opportunities above the optimal solution worsens the two other objective functions. In contrast to exergy reduction, profitability enhancement and job creation are contradictory. This contradiction is reasonable since the creation of job opportunities requires increased production, and increased production reduces profitability when it is not economically feasible. Moreover, the environmental impacts increased as the production increased at each echelon of the supply chain. In particular, 53 jobs can be created through a 1.5% reduction in profitability and a 2.2% rise in environmental impacts. These many job opportunities are significant.

C. Pricing decisions

Pricing decisions are crucial as Iran has a high inflation rate. To analyze the sensitivity of the model, it is required to measure its response to price variations. Fig. 4 shows the results of 108 model runs. The proposed supply chain had two mushroom types sold at different prices, depending on the demand. Therefore, it is required to separately evaluate the price of each mushroom type.

Table IV. Pareto-optimal solutions

Rows	*Percent*	*Profit * 10^6*	*Percentage change*	*Exergy losses*	*Percentage change*	*Job creation*	*Percentage change*
1	-90% Exergy	35.41	-80.21%	0.17375	-	55	-89.71%
2	-80% Exergy	61.86	-65.43%	0.34750	-	111	-79.45%
3	-70% Exergy	85.45	-52.25%	0.52125	-	166	-69.17%
4	-60% Exergy	107.26	-40.06%	0.69500	-	221	-58.90%
5	-50% Exergy	127.63	-28.67%	0.86876	-	277	-48.62%
6	-40% Exergy	144.43	-19.29%	1.04251	-	330	-38.68%
7	-30% Exergy	157.18	-12.16%	1.21626	-	384	-28.80%
8	-20% Exergy	168.10	-6.06%	1.39001	-	436	-19.01%
9	-10% Exergy	175.54	-1.90%	1.56376	-	486	-9.74%
10	Optimal solution	178.94	0%	1.73751	0%	539	0%
11	+10% Job creation	176.25	-1.50%	1.77567	2.20%	592	-
12	+20% Job creation	165.86	-7.31%	1.91122	10.00%	646	-
13	+30% Job creation	145.05	-18.94%	2.08361	19.92%	700	-
14	+37.68% Job creation	132.40	-26.01%	2.09726	20.70%	728	-

D. Demand stimulation strategies

The competition in the mushroom industry is intensive as its needs low initial investment. Thus, it is important to measure the impacts of demand on profitability. Moreover, the exergy loss and the number of created job opportunities are of great importance to supply chain decision-makers. This is addressed in the present study. Fig. 5 represents the results obtained from 36 model runs.

E. Equipment upgrade decisions

Supply chain decision-makers extremely need to have a clear idea of equipment upgrading and its impacts on profitability. This enables decision-makers to decide the upgrade of equipment based on a simple profit-cost model. Moreover, environmental impacts and job creation would affect such decisions. The upgrade of equipment boosts the production rate and capacity in the mushroom industry. Therefore, the present study performed 72 runs of the model to implement a sensitivity analysis on raising compost production and product yield, as shown in Fig 6.

V. RESULTS

Results of this article are divided into 4 parts. 1.Pricing, 2. Demand, 3. Equipment, and 4. Product selection.

A. Pricing

Fig. 4(a) depicts high-quality mushroom sales based on the demand. These sales account for a major portion of the supply chain income. Due to the low demand for the oyster mushroom, a 50% decline in its price would not significantly change supply chain profitability (only a 6% decline in the profit). However, a reduction in the button mushroom price substantially reduces the total profit (93%).

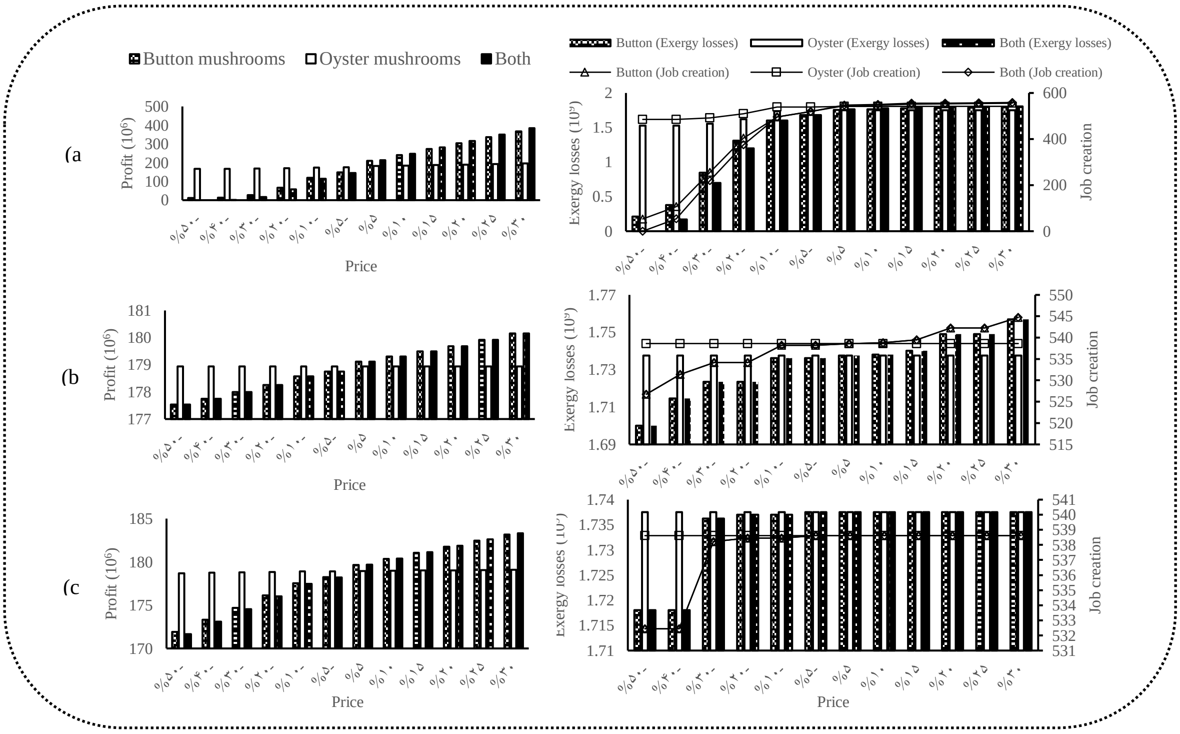

Fig 4. Selling price analysis for fulfilling demand mushrooms (a), exceeding demand mushrooms (b), and low-quality mushrooms (c)

As can be seen, the price of the button mushroom has significant effects on the prices of all the products (when both products undergo price rises or declines at the same time) since the button mushroom demand and production capacity are high. Also, the button mushroom had larger contributions than the oyster mushroom to job creation and exergy loss. The sales of excess mushrooms (Fig. 4(b)) and low-quality mushrooms (Fig. 4(c)) account for small portions of the income in the supply chain. Therefore, price changes would not have significant effects on profitability. In particular, profitability, exergy release, and job creation are heavily dependent on the button mushroom (for the aforementioned reasons). The produced oyster mushroom is entirely sold to meet the demand due to the low capacity of oyster mushroom compost production. Thus, a rise in the price of the excess mushroom is expectedly found to have no significant effect on the objective functions.

B. Demand

The supply chain is to supply 22,000 tons of mushrooms. The sensitivity analysis was carried out on the two mushroom types. As with pricing decisions, it was found that the profitability of the supply chain was dependent on the button mushroom. According to Fig. 5, the total profit response of the supply chain is dependent on the button mushroom demand, while changes in the demand for the oyster mushroom have no significant effects on the profit. This is also the case with exergy loss and job creation. The profitability of the supply chain remained almost unchanged when the oyster mushroom demand was incorporated, mainly due to the low production capacity of the oyster mushroom. Thus, the stimulation of the demand for the oyster mushroom alone would not change profitability, even though the oyster mushroom has a higher price. The same case holds for the exergy loss and the number of job opportunities created.

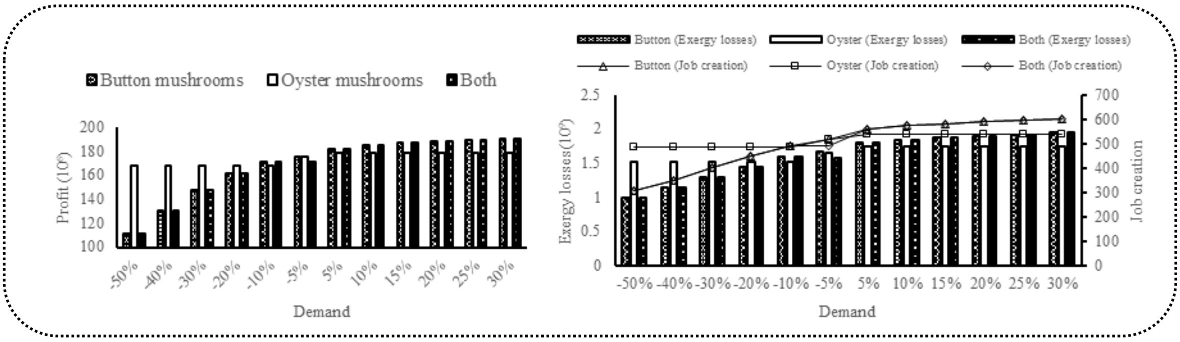

Fig 5. Demand analyzes

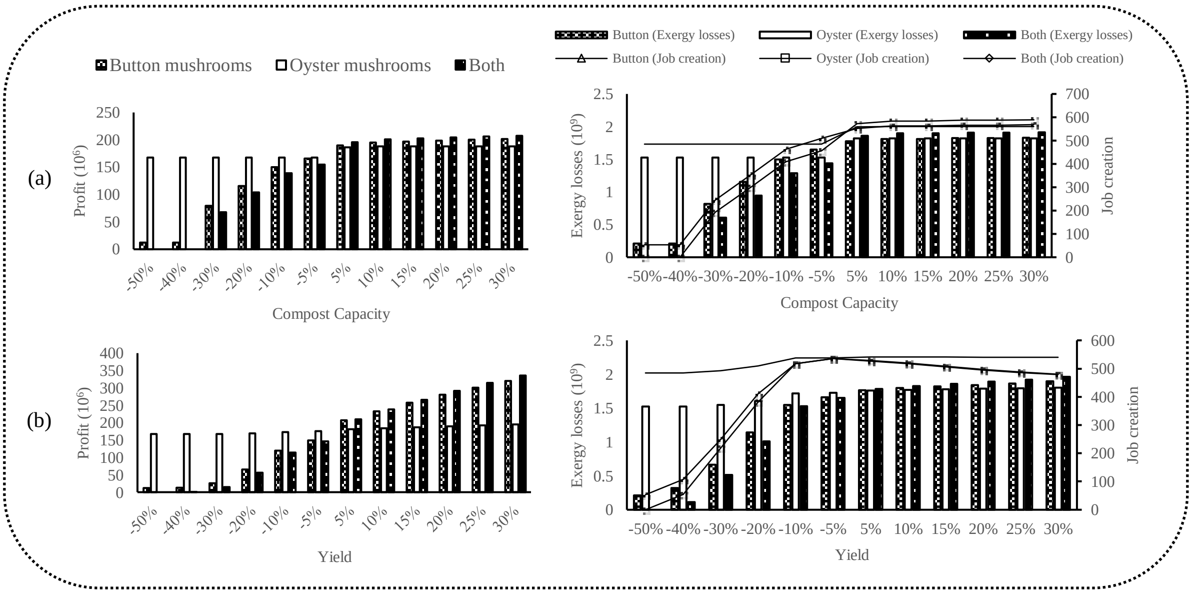

Fig 6. Compost production capacity analyze (a) and yield analyze (b)

C. Equipment

The two compost production centers have an annual capacity of 106,000 tons. Likewise, there is a significant relationship between the button mushroom and total profit, according to Fig. 6(a). The total profit substantially declines as the production capacity of the button mushroom reduces. Moreover, job creation and exergy loss are heavily dependent on the button mushroom. In particular, job creation is important under a rise in production capacity. The production of oyster mushroom compost requires more straw and stubble than that button mushroom compost. Thus, more job opportunities are created on the farms. As a result, compared to button mushroom compost, a rise in the production of oyster mushroom compost has a greater contribution to job creation; however, the contribution is insignificant since the button mushroom has a higher demand and a higher production capacity. The number of job opportunities created by raising the button mushroom production capacity exceeds those created by increasing the oyster mushroom production capacity only when the capacity is raised above 15%.

The product yield was evaluated as an improvement factor, as shown in Fig. 6(b). A rise in the yield of the button mushroom led to a much higher rise in the profit as compared to the oyster mushroom since the button mushroom has a higher demand and production capacity. This is also the case with exergy loss. However, job creation underwent a greater rise when the oyster mushroom yield increased. Interestingly, a rise in the button mushroom yield above a certain level reduces job creation. Job creation experiences the same trend when the yields of both mushrooms increases. The decline in job creation arises from reduced cultivation. Considering the optimal sales and increased product yields, the need for straw and stubble production decreases, decreasing the number of job opportunities. This job decrease is lower for the oyster mushroom. The increased yield of the oyster mushroom would not influence the production of the button mushroom as the dominant mushroom type since the oyster mushroom has a lower demand and compost production capacity. Therefore, an increase in the oyster mushroom yield results in a much lower reduction in job opportunities as compared to the button mushroom yield.

VI. PRODUCT SELECTION

This supply chain needs to select a product for development based on the three pillars of sustainability (i.e., economic, environmental, and social). Thus, 30 runs of the model were performed, as shown in Fig 7.

This study implemented product selection based on four factors, namely price, demand, compost production capacity, and product yield. As can be seen, investing in the button mushroom leads to much higher profitability than investing in the oyster mushroom. Also, the exergy loss is lower when investing in the button mushroom. However, the oyster mushroom results in more job opportunities since straw and stubble account for a large fraction of oyster mushroom compost, and the exergy loss of straw and stubble is higher than other materials, such as chicken manure. Therefore, the exergy loss of the oyster mushroom is higher than that of the button mushroom. Also, more job opportunities are created due to higher straw and stubble consumption. Overall, it can be concluded that investing in the button mushroom improves economic and environmental performances in the short run as compared to the oyster room.

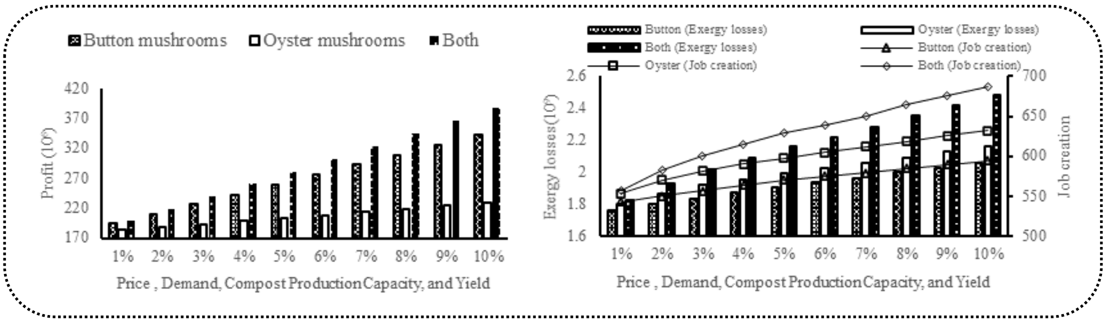

Fig 7. Product selection (simultaneous increase price, demand, compost production capacity, and yield)

To investigate the long-term outcomes of decisions, product selection was evaluated from a different perspective by replacing the price, demand, compost production capacity, and mushroom yield per ton of button compost with those of oyster mushroom compost. This increased profitability and job creation by 0.728% and 5.944%, respectively; however, the exergy loss increased by 53.84%. Excluding the price, the profit, exergy loss, and job creation increased by 53.23%, 77%, and 17.16%, respectively. Thus, assuming the price of the oyster mushroom to remain unchanged, the mass production of the oyster mushroom is economically and socially efficient, but the exergy loss significantly rises. Indeed, the increased profit arises from the increased price, increased exergy loss results from the use of straw and stubble in compost production, and the larger number of job opportunities stems from increased straw and stubble production in the farms. It is a time-consuming process to change the taste of consumers and induce a new demand. Thus, such a change would occur in the long run, and the provided analyses are suitable for long-term plans.

VII. CONCLUSION

The agricultural industry has long encountered many challenges, such as water deficiency, farmland shortage, environmental damage, agricultural employment, and irreparable damage to natural resources. At the same time, the global population has been increasing. Thus, food production is required to be increased by 70% in 2050 to feed the population of world (Alexandratos and Bruinsma, 2012). The proposed model is an efficient and effective framework that helps agri-food supply chain decision-makers in the mushroom industry evaluate their decisions from different perspectives. The novelty of the present work lies in a sustainable four-echelon supply chain model for agricultural industries, particularly the mushroom industry, with products of the same cultivation period. The proposed model incorporates uncertain product demand and yield. It also involves a secondary market that would purchase waste produced at the first three echelons. A sensitivity analysis was carried out on the mushroom supply chain with three farms, two compost production centers, and three mushroom cultivation centers.

The model was implemented on real-life data from the mushroom industry. It was found that the profitability of the button mushroom could be enhanced by raising the price, while the profitability of the oyster mushroom may be raised by increasing the compost production capacity. Since it has lower production costs than the button mushroom, the oyster mushroom has higher long-term economic efficiency. It consumes more straw and stubble and thus raises the number of job opportunities in the supply chain. However, the oyster mushroom has higher exergy loss than the button mushroom and thus has lower environmental efficiency. In general, the proposed model could be applied to crops that have the same cultivation period. In particular, the proposed model is applicable to the mushroom industry to evaluate the feasibility of producing different products. The mushroom industry can be assessed in economic, environmental, and social aspects using the proposed model at good reliability as it incorporates uncertainty. However, the present study did not consider uncertainty in the other parameters. The uncertainty of product prices, production costs, and environmental aspects can be taken into account in future research. Moreover, the model can be extended by adding more criteria in the economic, environmental, and social dimensions (e.g., land area used to cultivate crops, the food taste of the population, and production taxes), and also considering the food security problems. Finally, it is suggested that the proposed model be transformed into a closed-loop supply chain to measure the contributions of recycling to supply chain sustainability.

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