Applied Mathematical Modelling 112 (2022) 136–155

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

Crop planting and harvesting planning: Conceptual framework and sustainable multi-objective optimization for plants with variable molecule concentrations and minimum time between harvests

Ana Esteso[a,*], MME Alemany[a], Ángel Ortiz[a], Rina Iannacone[b]

[a] Research Centre on Production Management and Engineering (CIGIP), Universitat Politècnica de València, Camino de Vera S/N, Valencia 46022, Spain
[b] ALSIA-Metapontum Agrobios Research Center, S.S. Jonica 106, Km 448, 2, Metaponto, MT 75012 Italy

ARTICLE INFO

Article history:
Received 31 January 2022
Revised 5 June 2022
Accepted 19 July 2022
Available online 22 July 2022

Keyword:
Planting
Harvesting
Planning
Medicinal plants
Multi-objective optimization

ABSTRACT

The planting and harvesting of medicinal plants have characteristics that differentiate them from other crop types and complicate their planning. For example, drug processors do not require large quantities of product to be harvested but have a high concentration of active molecules. There is no evidence for any optimization tool to support the planting and harvesting of such plants. Given this sector's importance and its impact on populations' health, it is necessary to develop solutions to increase the sustainability of their supply chains. This paper aims to bridge this gap by proposing a conceptual framework to characterize a crop planting and harvesting planning problem, and a multi-objective optimization model for the planning of planting, harvesting, post-harvesting, distribution and storage of medicinal plants with variable concentrations of molecules and minimum time between harvests. The model optimizes three objectives aligned with sustainability: supply chain costs, concentration of molecules in plants, farmers' perceived economic unfairness. It is validated by its application to a case study of medicinal plants in the Basilicata region (Italy). The ε-constraint method is used to obtain 11 non dominated solutions showing the possibility of eliminating farmers' perception of economic unfairness by maintaining similar values for supply chain costs and concentrations of active molecules when planning the production of medicinal plants. Finally, the TOPSIS method is applied to select the best plan to be implemented into the supply chain.

1. Introduction

Multiple decision support models exist in the literature to support Crop Planting and Harvesting Planning (CPHP). Most consider that only fruit are harvested from plants, and leave aside other plant parts, such as leaves, flowers or roots, and that fruit are consumed in their natural form and do not usually require post-harvest activities. Although these models address similar CPHP problems, the characterization of the CPHP problem by considering differences in these processes

---

[*] Corresponding author.
E-mail address: aesteso@cigip.upv.es (A. Esteso).

https://doi.org/10.1016/j.apm.2022.07.023

according to the type of plant produced or the use of harvested crops is lacking. This paper bridges this gap by proposing a conceptual framework to characterize the CPHP problem, which is then used to review the most important models in the CPHP literature.

The findings of this review show that models to support CPHP for medicinal plants (MPs) do not exist. MPs have been traditionally used to treat diseases and to improve the health of both humans and animals [1]. However, their uses have been extended to other products, such as cosmetics and food supplements. MPs have been harvested from the wild for a long time [2], when they have been harvested from plants that naturally grew, which increased the risk of MPs becoming endangered [3]. To avoid this problem, and to better control MPs availability, and their organoleptic characteristics and prices, supply chains (SCs) began to plan their sustainable planting and harvesting.

However, MPs present some particularities related to planting, harvesting and post-harvest processes, plant yield behavior, the organizational relationship between farmers and processors, among others, that differentiate their management from that of other crop types (e.g., fresh fruit and vegetables). This confers additional complexities that, as far as we know, have not yet been addressed in the literature.

To bridge this gap, the present paper aims to propose a multi-objective mixed integer linear programming model to support sustainable CPHP for MPs from the economic, environmental and social points of view. In the MP SCs context, the sole traditional economic objective of agri-food SCs is no longer valid for being undermined by the goal of obtaining the maximum concentration of active molecules in harvested MPs, which will be used as raw material to produce drugs. Fulfilling this objective positively impacts environmental sustainability because for the same output (drugs quantity) it implies fewer requirements of inputs, such as natural resources (MCs, planting land areas and water), energy for plant drying and gas emissions from transport. Besides, due to specific organizational aspects of this type of SCs, a fair distribution of gains among farmers should be ensured as much as possible. Therefore, the sustainability of the planting and harvesting plan is ensured by the joint optimization of the three pillars of sustainability: maximizing the concentration of active molecules in the MPs delivered to the processor (environmental); minimizing SC costs (economic); minimizing economic unfairness among farmers (social).

The proposed model also considers that MPs can be harvested several times during their lifespan and the concentration of molecules varies when growing according to growth time, which is understood as the time between planting and first harvest, and between two consecutive harvests. Due to the dependence of MPs yields on the time between planting and first harvest, and between two consecutive harvests, the planning of planting and harvesting of this crop type should be modeled together. In addition, post-harvest activities like drying and sorting MPs and their transport to processing plants are modeled.

The multi-objective model is validated by its application to a natural food supplement SC in the Basilicata region of Italy. It is solved by the ε-constraint method along with the TOPSIS method to select the non dominated solution to be implemented. The results show the model's usefulness for achieving optimal solutions in a reasonable time for the type of addressed decisions.

The rest of the paper is structured as follows. Section 2 proposes a conceptual framework for the CPHP problem. This framework is used in Sections 3 and 4 to review previous optimization models for CPHP, and to characterize the problem under study, respectively. Section 5 formulates the multi-objective model to address the described CPHP problem. The model is validated, and the results are discussed in Section 6. Section 7 presents interesting managerial insights. Finally, Section 8 outlines the main conclusions and future research lines.

2. Conceptual framework for the CPHP problem

In order to simultaneously plan the planting and harvesting of crops, not only should the possible crops to be planted and the available planting area be considered, but also crops' nature and the characteristics of their harvests. Fig. 1 aims to characterize the CPHP problem along nine dimensions: crop use, plant lifespan, planting limitations, harvest dependence, harvest type, harvest frequency, harvest limitations, yield dependence, crop perishability.

Traditionally, crops are classified according to their lifespan into annuals, biennials and perennials [4]. Annual crops ensure their perpetuation by producing seeds in less than one-year. Biennial crops produce seeds in the second year of growth. Perennial crops continuously and indefinitely generate them [5]. Plants' lifespan determines their planting frequency and is, thus, related to farmers' exposure to risk. For example, erroneous planting decisions about annual crops are easier to solve than decisions made with perennials.

The planting process may be subject to limitations like those caused by weather (e.g., crops that require a certain temperature to be planted), soil composition and its suitability for each crop, or the requirement of planting a minimum area with the same crop due to technical aspects. In addition, when several crops can be planted it may be inappropriate to plant two varieties in adjacent areas in an attempt to preserve purity of varieties and to avoid crossbreeding (crop adjacency), or it may be appropriate to plant one crop or another depending on which crop was planted in the same area during previous periods (crop rotation).

The harvest period of crops can dependent, or not, on the planting period. Harvesting frequency depends on plants' nature. Some are harvested only once during their lifespan (e.g., onions), while others need to be harvested several times to continue their growth and fruit production (e.g., tomato plants). In the latter, a distinction can be made between continuous and discrete harvesting. In continuous harvest, plants are checked during every period to harvest ripe fruit and to release

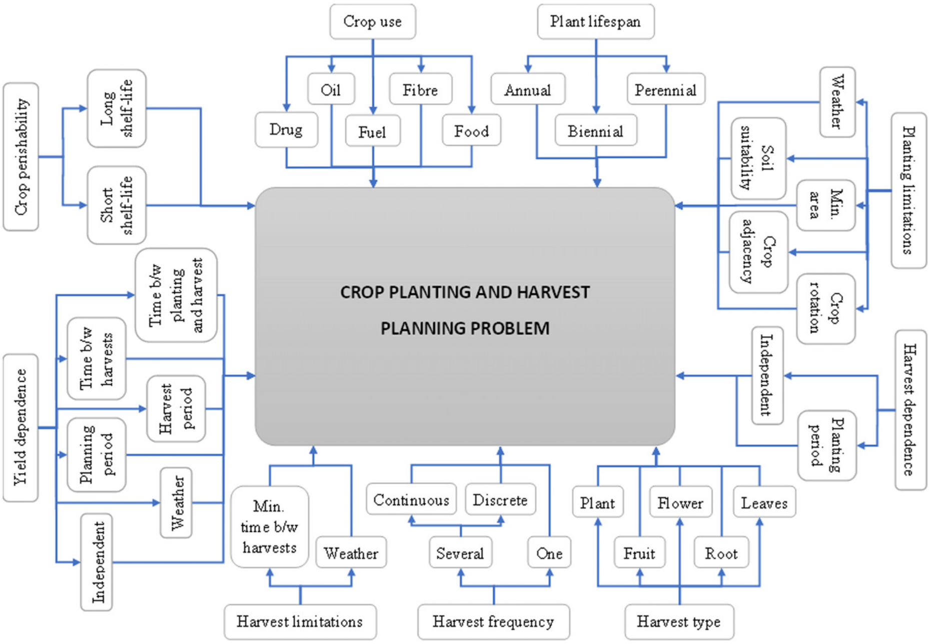

Fig. 1. Conceptual framework for the CPHP problem.

energy from plants to produce new fruit. Conversely in discrete harvests, crops are harvested several times throughout their lifespan in harvests separated by non harvest period. So a minimum time between harvests must be ensured.

The harvesting process can also be subject to limitations, such as this minimum time between consecutive harvests, or weather-related limitations (e.g., not possible to harvest a crop if it is raining or temperature is high).

Five harvesting types can be distinguished according to the plant part to be collected and required by consumers; fruit (e.g., strawberry), flowers (e.g., saffron), roots (e.g., ginger), leaves (e.g., tobacco), or the whole plant (e.g., green leafy vegetables). It is notable that the required plant part depends on the intended use of the harvest. For example with artichokes, the food industry requires only the fruit, while the drugs industry requests the whole plant. This underlines the importance of considering the intended use of crops when planning crop planting and harvest. Accordingly, crops can be used to produce food, fuel, fiber, oil and drugs [4]. Their use also determines the post-harvest activities that crops must undergo.

Plant yields can depend, or not, on planting and/or harvesting periods, on the time between planting and the first harvest, or on the time between two consecutive harvests (plant growth time). In crops with several continuous harvests, their yields usually depend on planting and/or harvesting periods. In crops with several discrete harvests, they normally depend on the plant growth time. Additionally, plant yields can depend on other non-temporal factors like weather.

Once harvested, crops can be classified as perishable or non-perishable. Crops are perishable when their shelf life is limited, decreases over time, and is shorter than the decision horizon. Perishability impacts crop management. Conversely, crops are non-perishable when their shelf life is longer than the decision horizon because their shelf life does not influence the decisions to be made.

3. Literature review

Based on the dimensions of the previous conceptual framework, in a structured way this section reviews existing optimization models for CPHP that have been published in scientific journals. This structured analysis of papers allows us to

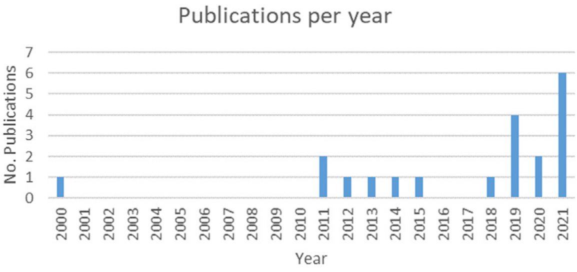

Fig. 2. Number of publications per year.

find out any research gaps and to identify the novelties of our proposal. Twenty research works published in the last 20 years are analyzed (Fig. 2). It is worth noting that 60% of these papers have been published in the last three years, which shows the growing interest in developing tools to support CPHP.

The 20 selected papers are studied through the proposed conceptual framework. Additionally, the main characteristics of their modeling are analyzed through the decision-making approach (centralized or distributed), the decision-making context (deterministic or uncertain), the number of SC stages, and the objectives that the models pursue.

Note that the intention is not to provide in-depth details for all the models' characteristics, but only those that are closely related to the problem under study. The results of the review are shown in Table 1, which also highlights the differences between existing models and that proposed in this paper. The characteristics covered only by this paper, which clearly represent the original contributions of our work, are marked in grey. Below a description of these results is provided.

In plant lifespan terms, most models are designed for the CPHP of annual crops, and only two models support this planning process for perennial crops, such as pome trees [26] and dragon fruit trees [23]. Therefore, no CPHP models designed for biannual crops appear, which represents a gap in the literature covered by this paper.

Regarding planting limitations, 50% of the papers consider a minimum area to be planted per crop during each period [12,23], or during the periods when it is decided to plant the crop [6,9–11,17,18,27,28], 5% consider land suitability for each crop, and 20% contemplate crop rotation-related limits. Therefore, some limitations in planting are not modeled in models to simultaneously plan crop planting and harvesting, such as the dependence of planting on weather or the consideration of crop adjacency.

Table 1
Literature review on CPHP models.

Dimension	Characteristic	Refs.	This paper	Total	%
Plant lifespan	Annual	[6–21]		16	80
	Biennial		X		
	Perennial	[22,23]		2	10
	Not indicated	[24,25]		2	10
Planting limitations	Weather				
	Minimum area	[6,9–12,14,16–18,23]		10	50
	Soil suitability	[25]		1	5
	Crop adjacency				
	Crop rotation	[12,13,15,19]		4	20
Crop use	Drug	[19]	X	1	5
	Food	[6–25]		20	100
	Fiber				
	Fuel				
	Oil				
Harvest dependence	Planting period	[6–11,13,14,16–18,22,23,25]	X	14	70
	Independent	[12,15,19–21,24]		6	30
Harvest type	Plant	[12,13,15,16,18,20,21]	X	7	35
	Fruit	[6–11,13–18,22–24,]		15	75
	Flowers				
	Roots				
	Leaves				
Harvest frequency	One	[12,13,19,21,25]		5	25
	Several discrete		X		
	Several continuous	[6–11,14–18,20,22–24]		15	75
Harvest limitations	Minimum time between harvests		X		
	Weather				
Yield dependence	Independent	[13,19,21]		3	15
	Weather	[17,18]		2	10
	Planting period	[6–11,14,16–18,23,25]		12	60
	Harvest period	[6–12,14–18,20,23,24]		15	75
	Time between harvests		X		
	Time between planting and harvest	[22,25]	X	2	10
Crop perishability	Short shelf life	[6–10,13–16,20]	X	10	50
	Long shelf life	[13,15]	X	2	10
	Not considered	[11,12,17–19,21–25]		10	50
Decision-making approach	Distributed	[9]		1	5
	Centralized	[6–25]	X	20	100
SC stage	Single-stage	[8,15,19,22,25]		5	25
	Bi-stage	[11,12,16,24]	X	4	20
	Multi-stage	[6,7,9,10,13,14,17,18,20,21,23]		12	60
Decision-making context	Deterministic	[6–8,10–13,16–19,21–23,25]	X	15	75
	Uncertain	[9,14,15,20,24]		5	25
Objectives	Economic	[6–25]	X	20	100
	Environmental	[11,19,20]	X	3	15
	Social	[11,19,25]	X	3	15

As for crop use, the analyzed models are intended for CPHP for food use, and models for fiber, fuel, oil and drug sectors are lacking. Only one of the analyzed models can be used in the drugs sector. However, its use is limited to cases in which the crops used to produce medicines are fruit that do not require post-harvest activities [19]. So this model does not take into account the nature and characteristics of MPs [19], unlike the model herein presented.

In terms of harvest-related dimensions, 70% of models consider that harvest depends on the period during which crops are planted (the harvest dependence dimension). As regards the harvest type dimension, most models consider harvesting fruit (75%), as in apples, dragon fruit, tomatoes or peppers, while others contemplate harvesting the whole plant (35%), as in green leafy vegetables, rice or sugar beet. Other harvesting types like harvesting flowers, roots and whole plants have not been previously modeled in the literature.

Regarding harvest frequency, harvesting is continuously carried out in cases in which fruit are harvested (75% of the models). This means that plants are checked during all the periods to harvest ripe fruit. The remaining models consider harvesting the whole plant and deal with crops harvested only once in their lifespan (e.g., wheat). However, no paper considers that harvesting continuously takes place, but discretely over time, which is another gap. As regards harvesting limitations, none of the analyzed models addresses them, and this is another area to be considered by future research. As shown in Table 1, our model addresses these two last gaps detected in the literature.

In yield dependence terms, models usually consider plant yield to depend on the planting and/or harvesting period (80%), while others consider that this yield also depends on the weather during the harvesting period (10%), the time between planting and harvesting (10%), or it does not depend on any factor (14%). However, none of the analyzed papers state that plant yield depends on the time between harvests, which is another of our contributions.

Most papers neither model the crop perishability characteristic (50%), nor consider that crops' shelf life is longer than the planning horizon (10%) and does not influence decision making. The other models consider that crops have a limited and shorter shelf life than the planning horizon.

For the decision-making approach, all the papers address centralized CPHP. Only Alemany et al. [9] also propose several distributed models with collaborative scenarios that represent farmers' usual planning behavior and, individually, crop planting and harvesting. They point out that centralized approaches are valid in those cases in which farmers have supply commitments with firms, which determines whether crop planning is to be implemented to balance supply and demand, which is the case of our paper.

Regarding the SC stages considered in the analyzed models, 25% of them consider a single-stage SC, while 20 and 55% of the models model two-stage and multistage SCs, respectively. In addition, most of the models contemplate a deterministic context for the decision-making process, while 25% of them consider the uncertainty that is inherent to the analyzed sectors, such as plant yields or the time required to perform agricultural activities.

Finally, on the objectives addressed by models, they all optimize economic measures by maximizing profits (85%) or minimizing costs (15%), while 15% of the papers also consider environmental and/or social objectives. Environmental objectives are related to water irrigation [19], fertilizer and pesticide use [19], energy use [19], CO_2 emissions [20], and the waste generated along the SC [11]. The social objectives are related to laboring [19], geographical diversification [25] and economic unfairness among famers [11]. Only one paper simultaneously considers economic and environmental objectives [20], one paper simultaneously includes socio-economic objectives [25], and two papers simultaneously consider economic, environmental and social objectives [11,19], although these objectives are not those optimized in this article.

The literature review reveals the existence of significant gaps in the models to support CPHP. The most relevant ones are related to the planning designed for biannual crops, and the consideration of either certain limitations in planting and harvesting processes, or the crops destined to produce fiber, oil or fuel. For modeling the crop harvesting process, gaps appear when considering the harvesting of flowers, roots or the whole plant for modeling of the frequency of harvesting when it occurs continuously and discretely, or plant yield dependence on the time between two harvests.

This paper aims to bridge some of these gaps, such as contemplating the biennial CPHP used to produce MPs, modeling several discrete harvests on the planning horizon, and plant yield dependence on a plant's growth time (time between planting and the first harvest, and time between two consecutive harvests). These are some of the main novelties of the proposed model. Furthermore, the proposed model is the first in the literature to optimize maximizing the concentration of active molecules in crops delivered to processors and to jointly optimize three objectives aligned with the three sustainability pillars: SC costs (economic), concentration of active molecules in crops (environmental) and unfairness among farmers (social).

4. Problem description

This paper focuses on solving the CPHP problem to be used in the drug sector where processors are not interested in acquiring large quantities of crops, but sufficient active molecules to be used as raw material in their production processes. Therefore, processors frequently and centrally plan the planting and harvesting to be implemented into SCs. This centralized planning reduces the crop overproduction and underproduction risk and its impact on prices.

In order to ensure that farmers implement the plan defined by processors, they sign collaboration contracts so that processors are committed to purchase the entire harvest obtained by farmers to, thus, reduce the risk of economic loss for farmers. In addition, by defining when planted crops are to be harvested, processors ensure that crops are harvested when the concentration of the required active molecules is at its maximum. Contracts also establish the post-harvest activities to be performed before deliveries are made to processors. In this case, these activities consist of drying crops during the same harvesting period to preserve the concentration of active molecules and sorting them by selecting the crop parts required by processors. These contracts are renewed every time planting and harvesting are to be planned.

The SC consists of several farmers, a central dryer, and a single producer with more than one location (Fig. 3). Farmers are responsible for planting, cultivating, and harvesting the area agreed with processors by means of a contract. Farmers dry crops during the same period as their harvest using their own dryer or the central dryer available to all farmers. Dried crops can be stored on farms indefinitely because once dried, they are no longer perishable, and their concentration of active molecules is stabilized. Farmers sort dry crops and store or transport them to processors where they can be stored until needed for production purposes.

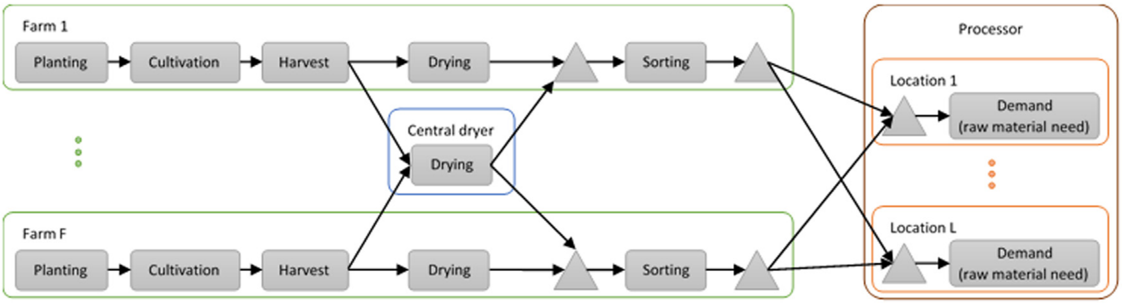

Fig. 3. SC configuration.

The characterization of the problem under study according to the proposed conceptual framework is shown in Fig. 4.

Crops are biennial and have no planting limitations. Their harvest depends on their planting period and often takes place throughout their lifespan. At each harvest the whole plants are harvested so that they grow back from their roots. Harvest

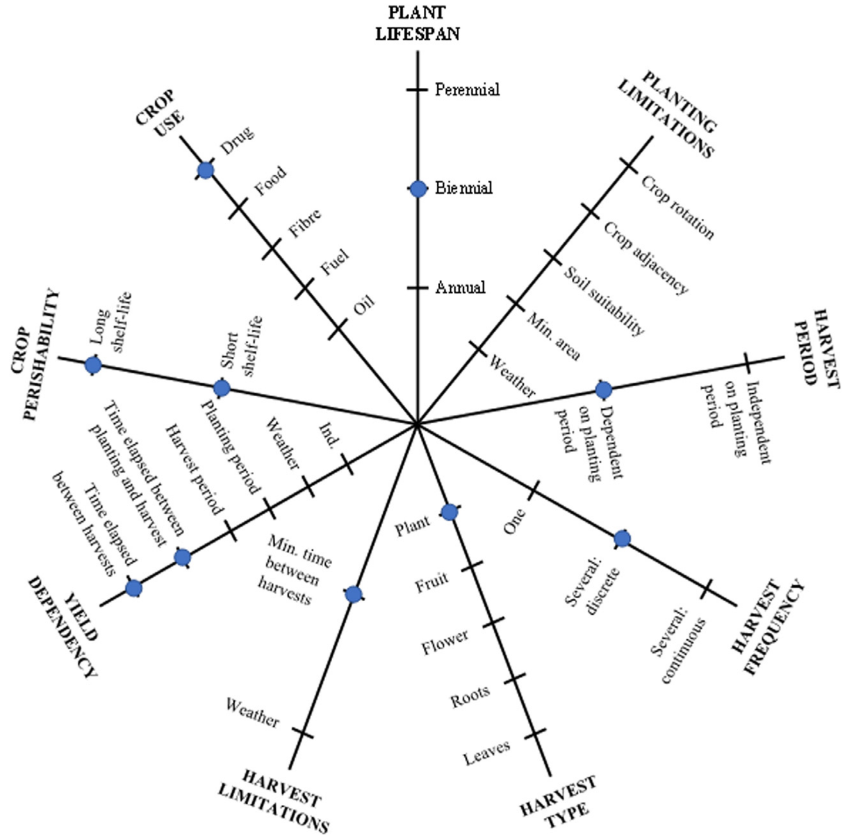

Fig. 4. Characterization of the problem under study.

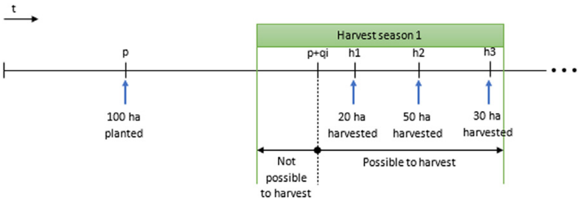

Fig. 5. Relation between planting and the first harvest season area.

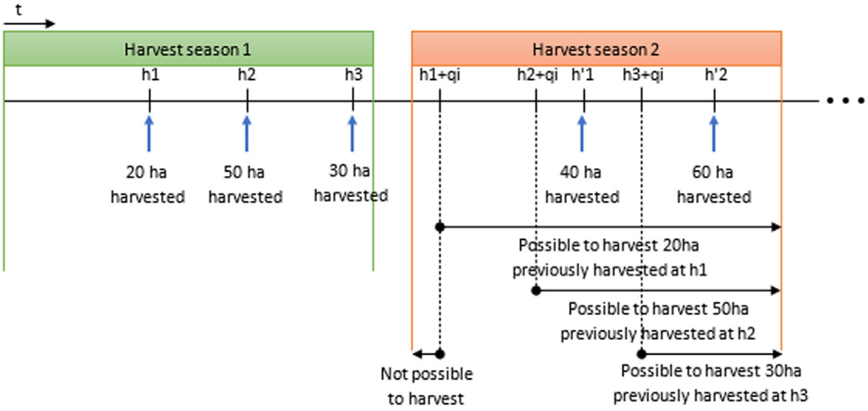

Fig. 6. Relation of area to be harvested during two consecutive harvesting seasons.

is limited by a minimum plant growth time before harvest to ensure the creation of active molecules. Once harvested, crops have a short shelf life, but their shelf life prolongs when they undergo the drying process.

In order to clarify the harvesting process, Fig. 5 shows an example in which 100 ha of a crop are planted during period p, and a minimum time q_i must be guaranteed between the planting period and the first harvest. It is not possible to harvest this area during the periods that belong to the first harvest season that are prior to $p+q_i$. Moreover, the 100 planted hectares must be harvested during one harvest or more, dated between period $p+q_i$ and the last period of the first harvest season.

During the following harvest seasons (Fig. 6), the planted area must have also been harvested by respecting the minimum time between consecutive harvests. Following the previous example, the 100 ha should be harvested during the second harvest season by respecting the minimum time between harvests. This means that the 20 ha harvested during period h_1 of the first harvest season can be harvested again during the periods belonging to the second harvest season above h_1+q_i. Similarly, the 50 and 30 harvested hectares during periods h_2 and h_3 of the first harvest season can be harvested during the periods of the second harvest season above h_2+q_i and h_3+q_i, respectively. Note that the number of harvests during two consecutive seasons does not necessarily have to be the same.

This paper proposes a multi-objective mathematical programming model to support the described problem, which works according to the following assumptions:

- CPHP is centrally defined by the processor who may have one facility or several.
- Contracts between processors and farmers establish the area to be planted per crop and farm, as well as the planting and harvesting periods. Processors purchase the whole harvest from farms.
- More than one crop can be planted on each farm. The same crop can be planted during different planting periods and on distinct areas. The same area can only be planted once along the horizon.
- There are as many harvest seasons for each crop as the number of harvests to be performed during a plant's lifespan. Crops are harvested once per harvest season.
- A minimum interval between planting and harvesting, and between consecutive harvests, must be ensured to guarantee plant growth and to create active molecules.
- Crop yield and concentration of active molecules depend on the plant growth time before harvest, which is the time between planting and the first harvest and, after that, between two consecutive harvests.
- Processors require harvested crops to be dried during the same harvesting period to avoid loss of active molecule concentration and to not shorten the crop shelf life. When dried, crops become non-perishable and the concentration of active molecules stabilizes.
- Crop weight lowers during drying because water evaporates, and also during sorting because unneeded plant parts are discarded.
- The capacity of not only farmers to dry, sort and store crops, but also of the central dryer, is limited.

- Dried sorted crops can be stored indefinitely by both farmers and processors.
- Farmers can transport crops to processors at any time, but a minimum amount must be transported for crops to be accepted. Farms and processors are close, so transport time is negligible.
- The crops SC aims to optimize three objectives aligned to sustainability: maximize the concentration of active molecules transported to processors (environmental); minimize SC costs (economic); minimize economic unfairness among farmers (social).

Environmental sustainability is defined as “the responsibility to conserve natural resources and protect global ecosystems to support health and wellbeing, now and in the future” [29]. Maximizing the concentration of active molecules can be considered an environmental objective for its positive and indirect impact on several factors that promote the SC’s environmental sustainability, especially those related to the preservation of natural resources.

To begin with, planning the planting area by projecting the active molecules that will be obtained in each plant, and choosing the time when the concentration is at its highest to harvest them, will require fewer plants being planted. Consequently, fewer natural resources, such as land and water, will be needed for this purpose, and it possible to use them for other purposes, such as nature preservation or fallow periods.

Smaller planting areas require fewer fertilizers, pesticides, among others, to plant, cultivate and harvest MPs, which improves environmental sustainability. In addition, the higher the concentration of active molecules per plant, the fewer plants to be dried. This reduces the energy required to perform this activity. Finally, obtaining more active molecules from fewer MPs means that less product must be transported from fields to processors and, thus, reduces transport, resulting CO_2 emissions and fuel use.

5. Mathematical programming model

The nomenclature employed to formulate the multi-objective mathematical programming model to solve the CPHP problem appears in Table 2 .

Table 2
Nomenclature.

Indices	
c	Crop.
f	Farm.
l	Processing plant.
p	Planting period.
$h,\ h'$	Harvest period.
s	Harvest season.
z	Plant growth interval by taking the value $z = h - p$ during the first harvest season or $z = h - h$’ during the next harvest seasons. Index h represents the crop harvest period, and h’denotes the period when the crop was harvested during the previous harvest season.
t	Period of time.
Set of indices	
P_c	Set of planting periods p during which crop c can be planted.
S_c	Set of harvest seasons s during which crop c should be harvested.
H_{cs}	Set of harvest periods h during which crop c can be harvested at season s.
Parameters	
a_f	Available area at farm f.
hi_c	Minimum interval between two harvests of crop c.
y_c^{sz}	Crop c yield during season s after z growing periods.
hd_c^{sz}	Weight conversion factor between the harvested and dry crop c if harvested during season s after z growing periods.
ds_c^{sz}	Percentage of the dry crop c weight that concentrates active molecules if harvested during season s after z growing periods. Represents the crop part requested by processors.
am_c^{sz}	Concentration of active molecules in one kilogram of dry sorted crop c if harvested during season s after z growing periods.
dc_f	Farm f’s drying capacity (kilograms).
dcc	The central dryer’s drying capacity (kilograms).
sc_f	Farm f’s sorting capacity (kilograms).
ic_f	Farm f’s storage capacity (kilograms).
ip_l	Processing plant l’s storage capacity (kilograms).
mt_{cl}	Minimum quantity of crop c to be transported to processor plant l if transported.
pc_c	Planting cost for one hectare of crop c.
ch_c	Harvest cost for one hectare of crop c.
cd_c	Drying cost for one kilogram of crop c at farms.
cdc_{cf}	Drying cost for one kilogram of crop c in the central dryer. Includes the cost of transporting the fresh crop from farm f to the central dryer, and the dry crop from the central dryer to farm f.
cs_c	Sorting cost for one kilogram of crop c.

(*continued on next page*)

Table 2 (*continued*)

Indices	
cif_c	Inventory cost per period for one kilogram of crop *c* on farms.
t_{cfl}	Transport cost for one kilogram of crop *c* from farm *f* to processing plant *l*.
cip_{cl}	Inventory cost per period for one kilogram of crop *c* in processing plant *l*.
pm_{cl}	Price paid by processing plant *l* to farms for one kilogram of crop *c*.
d^t_{cl}	Demand for dry sorted crop *c* in processing plant *l* during period t. This demand represents the raw material requirements of processing plant *l* to produce end products.
Decision variables	
AP^p_{cf}	Area planted with crop *c* on farm *f* during planting period *p*.
AH^{shz}_{cf}	Area of crop *c* harvested on farm *f* during period *h* of season *s* after *z* growing periods.
QH^{shz}_{cf}	Quantity of crop *c* harvested on farm *f* during period *h* of season *s* after *z* growing periods.
QD^{shz}_{cf}	Quantity of crop *c* dried on farm *f* during period *h* of season *s* after *z* growing periods.
QCD^{shz}_{cf}	Quantity of crop *c* of farm *f* dried in the central dryer during period *h* of season *s* after *z* growing periods.
ID^{shzt}_{cf}	Planned inventory of dried crop *c* on farm *f* during period *t* that was harvested during period *h* of season *s* after *z* growing periods (where $t \geq h + hi_c$).
QS^{shzt}_{cf}	Quantity of crop *c* harvested on farm *f* during period *h* of season *s* after *z* growing periods and sorted during period *t* (where $t \geq h + hi_c$).
IS^{shzt}_{cf}	Planned inventory of the dry sorted crop *c* on farm *f* during period *t* that was harvested during period *h* of season *s* after *z* growing periods (where $t \geq h + hi_c$).
QT^{shzt}_{cfl}	Quantity of the dry sorted crop *c* harvested during period *h* of season *s* after *z* growing periods and transported from farm *f* to processing plant *l* during period *t* (where $t \geq h + hi_c$).
YT^t_{cfl}	Binary decision variable whose value equals 1 when crop *c* is transported from farm *f* to processing plant *l* during period *t*.
I^t_{cl}	Planned inventory the dried sorted crop *c* at processing plant *l* during period *t*.
U_f	Economic unfairness of farm *f*.
Pr_f	Profit made by farm *f*.

5.1. Objectives

The model aims to simultaneously optimize three objectives aligned with the pillars of sustainability. The environmental objective (Z_A) consists of maximizing the concentration of active molecules in the crops acquired by processors, which depends on the quantity of the dried sorted crops transported to processors and the concentration of molecules in plants according to the plant growth time (1).

$$Max\ Z_A = \sum_c \sum_f \sum_l \sum_{s \in S_c} \sum_{h \in H_{cs}} \sum_{z \geq hi_c} \sum_{t \geq h} am^{sz}_c \cdot QT^{shzt}_{cfl} \tag{1}$$

The economic objective (Z_C) is to minimize the SC costs associated with planting, harvesting, drying, sorting, transporting and storing crops (2).

$$\begin{aligned} Min\ Z_C = &\sum_c \sum_f \sum_{p \in P_c} pc_c \cdot AP^p_{cf} + \sum_c \sum_f \sum_{s \in S_c} \sum_{h \in H_{cs}} \sum_{z \geq hi_c} ch_c \cdot AH^{shz}_{cf} \\ &+ \sum_c \sum_f \sum_{s \in S_c} \sum_{h \in H_{cs}} \sum_{z \geq hi_c} cd_c \cdot QD^{shz}_{cf} \\ &+ \sum_c \sum_f \sum_{s \in S_c} \sum_{h \in H_{cs}} \sum_{z \geq hi_c} cdc_{cf} \cdot QCD^{shz}_{cf} \\ &+ \sum_c \sum_f \sum_{s \in S_c} \sum_{h \in H_{cs}} \sum_{z \geq hi_c} \sum_{t \geq h} cs_c \cdot QS^{shzt}_{cf} \\ &+ \sum_c \sum_f \sum_{s \in S_c} \sum_{h \in H_{cs}} \sum_{z \geq hi_c} \sum_{t \geq h} cif_c \cdot \left(ID^{shzt}_{cf} + IS^{shzt}_{cf} \right) \\ &+ \sum_c \sum_f \sum_l \sum_{s \in S_c} \sum_{h \in H_{cs}} \sum_{z \geq hi_c} \sum_{t \geq h} ct_{cfl} \cdot QT^{shzt}_{cfl} \\ &+ \sum_c \sum_l \sum_z \sum_t cip_{cl} \cdot I^{zt}_{cl} \end{aligned} \tag{2}$$

The social objective (Z_U) consists in minimizing economic unfairness among farmers so that they consider it beneficial to sign contracts with processors. It is measured as the absolute difference between the profit made per hectare of each farmer and the average profit made per hectare of all the farmers (3). Profit includes the sale of crops to processors and the costs of planting, harvesting, drying, sorting, storing and transporting crops (4).

$$Min\ Z_U = \sum_f \left| \frac{\sum_{f'} \mathrm{Pr}_{f'}}{\sum_{f'} a_{f'}} - \frac{Pr_f}{a_f} \right| \tag{3}$$

$$\begin{aligned}
Pr_f = & \sum_c \sum_l \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} \sum_{t\geq h} \left(pm_{cl} - ct_{cfl}\right) \cdot QT_{cfl}^{shzt} - \sum_c \sum_{p\in P_c} pc_c \cdot AP_{cf}^{p} \\
& - \sum_c \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} ch_c \cdot AH_{cf}^{shz} - \sum_c \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} cd_c \cdot QD_{cf}^{shz} \\
& - \sum_c \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} cdc_{cf} \cdot QCD_{cf}^{shz} \\
& - \sum_c \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} \sum_{t\geq h} cs_c \cdot QS_{cf}^{shzt} \\
& - \sum_c \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} \sum_{t\geq h} cif_c \cdot \left(ID_{cf}^{shzt} + IS_{cf}^{shzt}\right) \qquad \forall f
\end{aligned} \tag{4}$$

5.2. Constraints

The model is subject to the following constraints. The area to be planted with all the crops per farm is limited by the area available on the farm (5) that can be planted only once along the horizon.

$$\sum_c \sum_{p\in P_c} AP_{cf}^{p} \leq a_f \qquad \forall f \tag{5}$$

The entire planted area must be harvested during all the harvest seasons to ensure a minimum time between planting and the first harvest (6), and between two consecutive harvests (7), so that active molecules develop in plants. This requires controlling the harvesting periods of the areas during each season, which increases the complexity of formulating and resolving this set of constraints.

$$AP_{cf}^{p} = \sum_{\substack{h\,\in\, H_{cs} \\ h\,\geq\, p+hi_c}} AH_{cf}^{sh\ z=h-p} \qquad \forall c, f, p \in P_c,\ s = 1 \tag{6}$$

$$\sum_{z'} AH_{cf}^{s-1\ hz'} = \sum_{\substack{h'\,\in\, H_{cs} \\ h'\,\geq\, h+hi_c}} AH_{cf}^{sh'\ z=h'-h} \qquad \forall c,\ f,\ s > 1,\ h \in H_{cs-1} \tag{7}$$

Harvest quantity depends on the planted area and plant yield, which varies according to the plant growth time before harvest (8).

$$QH_{cf}^{shz} = AH_{cf}^{shz} \cdot y_c^{sz} \qquad \forall c, f, s \in S_c,\ h \in H_{cs}, z \geq hi_c \tag{8}$$

The harvested crop must be dried during the same period of its harvest to stabilize its concentration of active molecules and transform crops into non-perishable ones (9). Therefore, the quantity of the crop to be harvested during each period is limited by the farmer's own dryer's drying capacity (10) and the central dryer's capacity (11).

$$QH_{cf}^{shz} = QD_{cf}^{shz} + QCD_{cf}^{shz} \qquad \forall c, f, s \in S_c,\ h \in H_{cs},\ z \geq hi_c \tag{9}$$

$$\sum_c \sum_{s\in S_c} \sum_{z\geq hi_c} QD_{cf}^{shz} \leq dc_f \qquad \forall f, h \tag{10}$$

$$\sum_c \sum_f \sum_{s\in S_c} \sum_{z\geq hi_c} QCD_{cf}^{shz} \leq dcc \qquad \forall h \tag{11}$$

Dried crops can be stored indefinitely until sorted. The inventory balance for the same harvest period is defined in (12), while the balance for the following periods is calculated in (13). These equations consider the weight loss of the harvested crops during the drying process due to water evaporation.

$$ID_{cf}^{shzt} = QD_{cf}^{shz} \cdot hd_c^{sz} + QCD_{cf}^{shz} \cdot hd_c^{sz} - QS_{cf}^{shzt} \qquad \forall c, f, s \in S_c, h \in H_{cs}, z \geq hi_c, t = h \tag{12}$$

$$ID_{cf}^{shzt} = ID_{cf}^{shzt-1} - QS_{cf}^{shzt} \qquad \forall c, f, s \in S_c, h \in H_{cs}, z \geq hi_c, t > h \tag{13}$$

The sorting process of dried crops is limited by farmers' capacity for this activity (14).

$$\sum_c \sum_{s\in S_c} \sum_{\substack{h\,\in\, H_{cs} \\ h\,\leq\, t}} \sum_{z\geq hi_c} QS_{cf}^{shzt} \leq sc_f \qquad \forall f, t \tag{14}$$

The dried sorted crops can be stored again indefinitely until they are transported to processors (15). This equation considers the weight loss of crops because the plant parts not required by processors are discarded.

$$IS_{cf}^{shzt} = IS_{cf}^{shzt-1} + QS_{cf}^{shzt} \cdot ds_c^{sz} - \sum_l QT_{cfl}^{shzt} \quad \forall c, f, s \in S_c, h \in H_{cs}, z \geq hi_c,\ \ t \geq h \tag{15}$$

The inventory of the dried crops, and the dried sorted crops, is limited by farmers' storage capacity (16).

$$\sum_c \sum_{s\in H_c} \sum_{\substack{h \in H_{cs} \\ h \leq t}} \sum_{z \geq hi_c} \left(ID_{cf}^{shzt} + IS_{cf}^{shzt} \right) \leq ic_f \qquad \forall f, t \tag{16}$$

When transporting a crop to processors, a minimum quantity must be transported for it to be accepted (17). The set of constraints (18) regulates the operation of the binary variable that takes a value of one when a crop is transported from a farm to a processor.

$$\sum_{s\in S_c} \sum_{\substack{h \in H_{cs} \\ h \leq t}} \sum_{z \geq hi_c} QT_{cfl}^{shzt} \geq YT_{cfl}^{t} \cdot mt_c \qquad \forall c, f, l,\ t \tag{17}$$

$$\sum_{s\in S_c} \sum_{\substack{h \in H_{cs} \\ h \leq t}} \sum_{z \geq hi_c} QT_{cfl}^{shzt} \leq YT_{cfl}^{t} \cdot d_{cl}^{t} \qquad \forall c, f, l,\ t \tag{18}$$

The crop transported to a processor is either used as raw materials to produce end products or is stored until needed for production (19).

$$I_{cl}^{t} = I_{cl}^{t-1} + \sum_f \sum_{s\in S_c} \sum_{\substack{h \in H_{sc} \\ h \leq t}} \sum_{z \geq hi_c} QT_{cfl}^{shzt} - d_{cl}^{t} \qquad \forall c, l, t \tag{19}$$

Finally, the nature of the employed decision variables is defined (20).

$$\begin{array}{cc} AP_{cf}^{p},\ AH_{cf}^{shz},\ QH_{cf}^{shz}, QD_{cf}^{shz}, QCD_{cf}^{shz}, ID_{cf}^{shzt},\ QS_{cf}^{shzt},\ IS_{cf}^{shzt},\ QT_{cfl}^{shzt},\ I_{cl}^{t} & CONTINUOUS \\ YT_{cfl}^{t} & BINARY \end{array} \tag{20}$$

5.3. Resolution methodology

In order to solve the proposed model, it is necessary to linearize objective Z_U related to the minimization of economic unfairness among farmers (3). For this purpose, the transformation proposed in [11] is applied, and Eqs. (21)–(23) are obtained.

$$Min\ Z_U = \sum_f U_f \tag{21}$$

$$U_f \geq \frac{\sum_{f'} Pr_{f'}}{\sum_{f'} a_{f'}} - \frac{Pr_f}{a_f} \qquad \forall f \tag{22}$$

$$U_f \geq \frac{Pr_f}{a_f} - \frac{\sum_{f'} Pr_{f'}}{\sum_{f'} a_{f'}} \qquad \forall f \tag{23}$$

The ε-constraint method [30] is followed to transform the multi-objective model into a single-objective model by keeping the maximization of the concentration of active molecules as the model's objective function (1a), and transforming the other objectives into constraints (24–25). The new model is formulated as follows:

$$Min\ Z_A \tag{1a}$$

subject to:

$$\begin{aligned}
&\sum_c \sum_f \sum_{p\in P_c} pc_c \cdot AP_{cf}^{p} + \sum_c \sum_f \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} ch_c \cdot AH_{cf}^{shz} \\
&+ \sum_c \sum_f \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} cd_c \cdot QD_{cf}^{shz} \\
&+ \sum_c \sum_f \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} cdc_{cf} \cdot QCD_{cf}^{shz} \\
&+ \sum_c \sum_f \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} \sum_{t\geq h} cs_c \cdot QS_{cf}^{shzt} \\
&+ \sum_c \sum_f \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} \sum_{t\geq h} cif_c \cdot \left(ID_{cf}^{shzt} + IS_{cf}^{shzt}\right) \\
&+ \sum_c \sum_f \sum_l \sum_{s\in S_c} \sum_{h\in H_{cs}} \sum_{z\geq hi_c} \sum_{t\geq h} ct_{cfl} \cdot QT_{cfl}^{shzt} \\
&+ \sum_c \sum_l \sum_z \sum_t cip_{cl} \cdot I_{cl}^{zt} \leq \varepsilon_C
\end{aligned} \tag{24}$$

$$\sum_f U_f \leq \varepsilon_U \tag{25}$$

and Eqs. (4)–(20), (22), (23)

With this model, several non-dominated solutions can be obtained by employing multiple values for parameters ε_C and ε_U. However, only one solution must be selected to be finally implemented into the real SC. To put this selection into practice, the TOPSIS method [31] is employed.

6. Computational experiments

This section aims to validate the proposed model by applying it to the case study of MPs in Basilicata (Italy) where a processor of natural food supplements intends to plan the planting of MPs on ten farms. The processor is interested in planting lemon balm and sage because the rosmarinic acid extracted from them is one of its main raw materials.

Although lemon balm and sage are perennial crops, they only provide a sufficient concentration of rosmarinic acid the first two years after planting. So processors consider them to be biennial. Therefore, a 2-year planning horizon with 104 weekly periods is considered, on which lemon balm and sage plants are harvested several times. After this horizon, plants are pulled up and soil is prepared for the next planting season. Fig. 7 shows the planting and harvesting calendar of lemon balm and sage in southern Italy, where they are normally planted late in April or early in May (weeks 17–20).

These MPs are harvested by mowing plants. Subsequently, plants are regrown from roots and the small trunks remaining from the previous harvest. With lemon balm, harvesting is done twice the first year and up to four times in the second year to ensure a minimum of seven weeks between harvests to guarantee plant growth and to create rosmarinic acid. Sage is harvested once the first year and a maximum of three times the second year to ensure a minimum of nine weeks between harvests.

The yield of these MPs varies depending on plants' growth time. The conversion between one kilogram of fresh MP and one kilogram of dried MP is variable because plants have different water concentrations depending on the weather. This leads to the loss of different masses during the same drying process. Finally, the percentage of plant mass that concentrates rosmarinic acid in the dried sorted plant also depends on the plant growth time and harvest season. Although the data for these parameters are known by the processor, only the minimum and maximum values are shown for confidentiality reasons (Table 3). It should also be noted that these values do not necessarily correspond to the same growth time or harvest season.

The area available for planting MPs on the 10 farms, as well as the storage capacity per farm, the cost of transporting MPs to the processor and the cost of drying in the central dryer, are provided in Table 4. The cost of drying in the central dryer includes the costs of transporting products from the farm to the central dryer, and back again. All the farmers have a drying and sorting capacity of 2000 and 2000 kg/week, respectively. The central dryer has a drying capacity of 2000 kg per

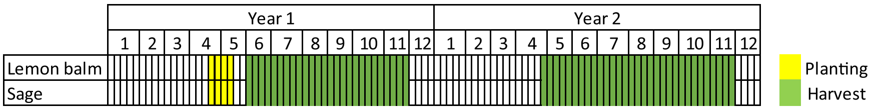

Fig. 7. Planting and harvest calendar for medicinal plants.

Table 3
Information about MPs.

MP	Yield per mowing (kg/ha)	Fresh to dry conversion	Percentage of plant with rosmarinic acid	Rosmarinic acid concentration
Lemon balm	8665–9400	19–27%	97–99%	1.4–2.8%
Sage	5333–10000	20–33%	97–99%	1.9–3.9%

Table 4
Capacity and costs of farming resources.

Farm	Area (ha)	Storage capacity (kg/week)	Transport cost (€/kg)	Drying cost of the central dryer (€/kg)
1	1.4	2400	0.54	1.11
2	1.8	2900	0.68	1.28
3	0.7	2800	0.61	1.18
4	1.4	2100	0.56	1.23
5	1.7	2000	0.55	1.26
6	1.5	3000	0.68	1.15
7	0.9	2200	0.50	1.23
8	1.2	2500	0.70	1.16
9	0.8	2400	0.65	1.21
10	0.6	2000	0.67	1.24

Table 5
Economic data.

MP	Price (€/kg)	Planting cost (€/ha)	Harvest cost (€/ha)	Drying cost on farm (€/kg)	Sorting cost (€/kg)	Storage cost on farm (€/kg·week)	Storage cost at the processor (€/kg·week)
Lemon balm	3.30	4000	866.25	1.00	0.05	0.015	0.015
Sage	3.50	3150	1155	1.00	0.05	0.015	0.015

period. In addition, a minimum of 50 kg of the same MP must be transported to the processor to be accepted. In addition, different MPs can be transported in the same vehicle. The processor's storage capacity is limited to 50,000 kg of the dried sorted MPs.

The costs related to the planting, harvesting, drying, sorting and storage of MPs are found in Table 5.

6.1. Results

In order to solve the model using the ε-constraint method, it is necessary to determine ε-values. Lexicographic optimization was used for this purpose [11], which consists of optimizing the model's objectives one by one by fixing the value of the previously optimized objectives (Table 6). These values can be used to check that the optimized objectives are not aligned or conflictive, which is a prerequisite for applying a multi-objective approach.

To check whether the objectives are aligned, a partial correlation analysis is performed between the lexicographic optimization results (Table 7). Two objectives are aligned when the improvement of one necessarily implies the improvement of the other. For such situations, correlation index values higher than 0.9 are obtained for the objectives optimized in the same direction (maximization-maximization or minimization-minimization), or lower than -0.9 for the objectives optimized in the opposite direction (minimization-maximization) [11].

Based on the previous properties, Table 7 shows that the correlation index between Z_A and Z_C equals one. So an increase in the Z_A value leads to an increase in the Z_C. value. In this case, as Z_A is maximized and Z_C is minimized, the objectives are conflictive because the improvement of one implies the other worsening. As there is no clear correlation between the other pairs of objectives (Z_A-Z_U and Z_C-Z_U), they are not aligned, and the use of the multi-objective approach is approved.

Table 6
Lexicographic optimization.

Optimization order	Z_A	Z_C	Z_U
$Z_A \rightarrow Z_C \rightarrow Z_U$	1713.12	273282.25	4402.67
$Z_A \rightarrow Z_U \rightarrow Z_C$	1713.12	274227.66	797.61
$Z_C \rightarrow Z_A \rightarrow Z_U$	592.32	117589.17	12073.11
$Z_C \rightarrow Z_U \rightarrow Z_A$	592.30	117589.17	11598.11
$Z_U \rightarrow Z_A \rightarrow Z_C$	1637.65	269250.84	0.00
$Z_U \rightarrow Z_C \rightarrow Z_A$	592.53	117900.28	0.00

Table 7
Partial correlation analysis for non-dominated solutions.

	Z_A	Z_C	Z_U
Z_A	1.00	1.00	- 0.57
Z_C	1.00	1.00	- 0.57
Z_U	- 0.57	- 0.57	1.00

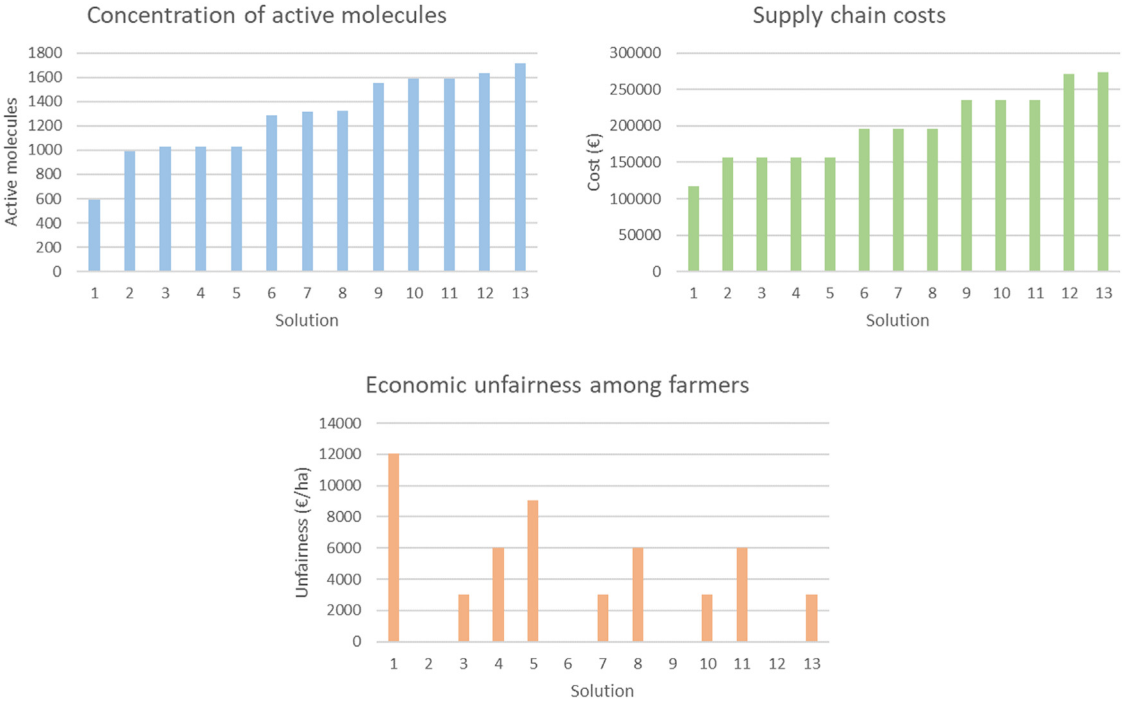

Fig. 8. Results for the ε-constraint resolution.

The minimum and maximum values obtained for each objective in the lexicographic optimization are employed as the lowest and highest ε-values related to these objectives, respectively. Additionally, as many ε-values as desired can be obtained by dividing this range into equal intervals.

The model is solved for 25 scenarios, obtained by combining five ε-values for the SC costs (ε_C) and economic unfairness (ε_U) objectives. One remarkable finding is that not all the ε-values combinations provide solutions because some combinations are infeasible. After solving the model, 13 non-dominated solutions (numbered from 1 to 13) are obtained and analyzed in terms of the concentration of active molecules, SC costs and unfairness among farmers (Fig. 8).

The results show how maximizing the concentration of active molecules in the MPs delivered to the processor implies considerably increasing the SC costs. In addition, different values for economic unfairness among farmers are obtained for similar values of the SC costs and the concentration of active molecules. For example, solutions 5–7 obtain SC costs close to 195908 € and the concentration of active molecules ranges from 1283 to 1321, while economic unfairness among farmers ranges from 0 to 6036 €/ha. This means that it is possible to considerably reduce economic unfairness among farmers by maintaining the values of the SC costs and slightly varying the concentration of the active molecules delivered to the company. So it would be advisable for farmers to be willing to sign contracts with processors and to form part of this centralized planning.

These results provide processors with several options for the CPHP to be carried out with their contracted farmers insofar as, depending on whether it is more important for the processor to obtain a higher concentration of active molecules or to reduce SC costs, the processor could choose a different plan to be implemented.

To select the solution to be implemented into the SC, this paper uses the TOPSIS method, a multicriteria decision analysis method that aims to select the alternative with a shorter geometric distance to the positive ideal solution, and a longer geometric distance to the negative ideal solution [31]. To apply this method, a matrix composed of the alternatives and their values for the selection criteria is constructed. In this paper, the selection criteria correspond to the three optimized objectives, and the alternatives are the 13 solutions generated by the ε-constraint method. This matrix is linearly normalized according to [31], and the weighted normalized matrix (Table 8) is constructed by assigning to the normalized values a weight that, in this case, is the same for all three criteria ($w_A = w_C = w_U = 0.\widehat{33}$). The positive ($t_{bj}$) and the negative ($t_{wj}$) ideal solution for each criterion are identified as the best and worst values of this matrix, respectively.

The distance of each solution to the positive (d_{ib}) and negative (d_{iw}) ideal alternatives, as well as the relative proximity of each solution to the ideal alternative (s_i), are calculated in Table 9 as defined in [31].

The solution with a higher s_i value has a closer proximity to the ideal alternative and is selected for the application in the SC (Table 9). In this case, planning 6 is selected, in which a high concentration of active molecules and moderate costs are obtained in the SC, while eliminating farmers' perceived economic unfairness.

The planning of the planting, harvesting and distribution of the crops obtained in Solution 6 chosen for its application in the SC is shown in more detail below. Fig. 9 shows the planning of the proportion of area to be planted with each crop on

Table 8
Normalized and weighted normalized matrix.

Normalized matrix				Weighted normalized matrix			
Solution	Z_A	Z_C	Z_U	Solution	Z_A	Z_C	Z_U
1	0.124	0.160	0.625	1	0.041	0.053	0.208
2	0.207	0.213	0.000	2	0.069	0.071	0.000
3	0.216	0.213	0.156	3	0.072	0.071	0.052
4	0.216	0.213	0.312	4	0.072	0.071	0.104
5	0.216	0.213	0.469	5	0.072	0.071	0.156
6	0.269	0.266	0.000	6	0.090	0.089	0.000
7	0.277	0.266	0.156	7	0.092	0.089	0.052
8	0.277	0.266	0.312	8	0.092	0.089	0.104
9	0.326	0.319	0.000	9	0.109	0.106	0.000
10	0.334	0.319	0.156	10	0.111	0.106	0.052
11	0.334	0.319	0.312	11	0.111	0.106	0.104
12	0.343	0.369	0.000	12	0.114	0.123	0.000
13	0.359	0.373	0.156	13	0.120	0.124	0.052
				t_{bj}	0.120	0.053	0.000
				t_{wj}	0.041	0.124	0.208

Table 9
Distance and proximity matrix.

Solution	d_{ib}	d_{iw}	s_i
1	0.222	0.071	0.242
2	0.054	0.217	0.802
3	0.073	0.168	0.697
4	0.116	0.121	0.510
5	0.164	0.080	0.329
6	0.046	0.217	0.823
7	0.069	0.168	0.710
8	0.113	0.121	0.517
9	0.054	0.220	0.802
10	0.075	0.172	0.697
11	0.117	0.127	0.519
12	0.070	0.221	0.760
13	0.088	0.175	0.665

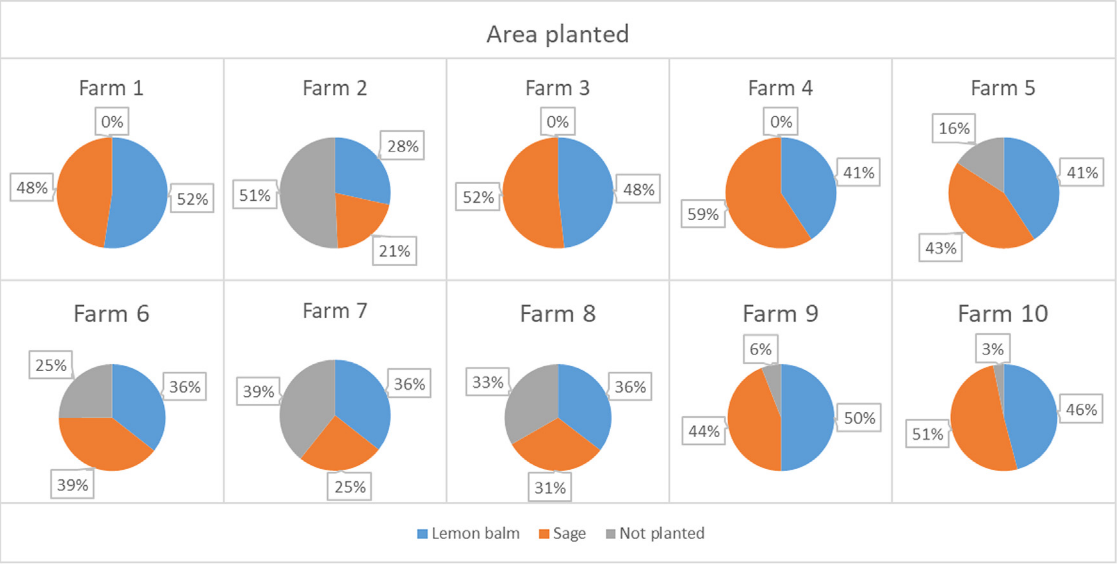

Fig. 9. Planned area to be planted on farms (Solution 6).

each farm. According to this solution, lemon balm and sage are planned to be planted on all the farms, albeit in different proportions.

Fig. 10 shows the planned planting and harvesting schedule for each crop on all the farms. Planting crops is planned in week 17 on all the farms, which is the first week when this activity is allowed for both crops.

Fig. 10. Planned planting and harvesting schedule per farm (Solution 6).

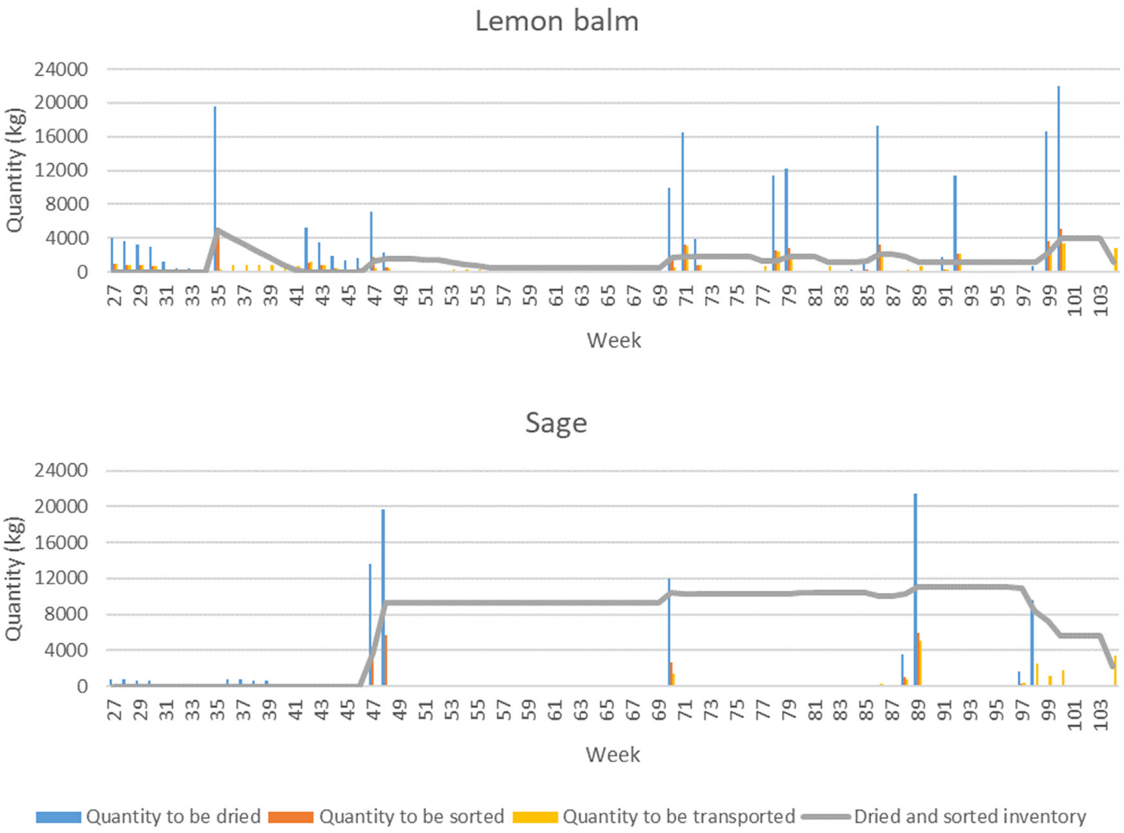

Fig. 11. Planning the post-harvest activities, inventory and transport of crops (Solution 6).

The harvesting schedule is different for each farm and crop. On most farms and during most seasons, the area planted with lemon balm is planned to be harvested during several periods to, thus, balance farmers' burden with this task. However, on some farms where the area planted with lemon balm is small (up to 0.4 ha), the whole planted area is planned to be harvested in one week.

For sage, the entire planted area is planned to be harvested during several periods of the same season in the first year. In most seasons of the second year, the entire planted area is planned to be harvested in one week of each season as long as the farm has sufficient capacity to dry all the harvested product.

Finally, Fig. 11 displays the planning of the quantity of crop to be dried and sorted every week, the quantity of the dried sorted crop to be stored, and the quantity of the dried sorted crop to be transported to the processor.

It is remarkable that the weight of MPs lowers during both the drying process due to loss of water and the sorting process because the plant parts that do not contain active molecules are discarded.

The results show for many weeks that the same quantity of crop is dried, sorted and transported to the processor, and the inventory of these crops on the farm remains constant. On the contrary, in the weeks when a larger quantity is planned to be sorted than transported, the inventory increases. In the weeks when a smaller quantity is planned to be sorted than transported, the inventory decreases.

6.2. Computational efficiency

The model has been implemented in the optimization program MPL Modeling System® Release 5.0.8.116 and solved with solver Gurobi Optimization 9.1.1. The input data are imported from a database generated in a Microsoft Access Database. The values obtained for the decision variables are exported to this same database. A computer with a processor Intel® Xeon® CPU E5-2640 v2 @ 2.00 GHz 2.00 GHz (two processors) and installed capacity of 32 GB and a 64-bit operating system was used to solve the proposed model.

For the case study, the proposed multi-objective model resulted in 292717 constraints and 413844 decision variables, of which 412804 were continuous and 1040 were binary.

The model's resolution time was limited to three hours (180 min). Fig. 12 shows the resolution time for the 13 solutions found. Only in five cases was the optimal solution obtained in less than three hours (solutions 5, 6, 10, 11 and 13). However, it is worth noting that on six occasions (solutions 2, 3, 4, 6, 7 and 9), the model returned a solution when the time limit

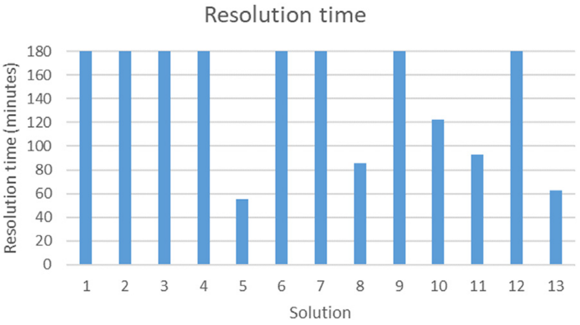

Fig. 12. Resolution time for optimal solutions.

was reached, which has a gap, and was calculated as the percentage difference of the found solution in relation to the best analyzed bound, at less than 0.05% and with an average gap of 0.02%. These results suggest that they are optimal or near-optimal solutions.

7. Managerial insights

The model herein proposed was inspired in a real-life problem of an important company that produces food supplements in the Basilicata region of Italy, which validated the obtained results. The generalizations and abstraction made while formulating the model allowed it to be used for any SC integrated by several farmers, one central dryer and a processor with production plants in different locations.

The model is designed to be executed by companies that produce medicinal or non-medicinal products, where the concentration of certain active molecules in the plants used as raw material is relevant, and who have sufficient power in the SC to make centralized decisions that affect farmers. This is because the model can be used to not only plan the planting and harvesting of MPs, but also the activities that must be performed until the processor acquires MPs, or to replan some of these activities.

The main advantage of this model lies in the fact that it incorporates characteristics of MPs production that have not been considered in previous models found in the literature, such as the existence of a minimum plant growth time before harvest, the dependence of plant yield and the concentration of active molecules in plants on the growth time, which are of extremely relevant for the medicinal sector. In contrast, the existing models for CPHP in the literature are unsuitable for solving the problem under study because, by not modeling these distinctive characteristics of MPs, they can provide inadequate, or even infeasible, planning.

By running the model, managers acquire very valuable information to support their decisions. Indeed the model's results provide managers with a set of non-dominated solutions as regards the three sustainable objectives to decide on the CPHP of MPs. Having more than one satisfactory solution to be implemented is an advantage for managers, who should select (preferably in a collaborative way with farmers) the most satisfactory one to be implemented into the SC. Managers of processing companies are provided with different sustainable plans for planting, harvesting and distribution plans because the model attempts to simultaneously optimize the concentration of active molecules in purchased MPs (environmental), minimize SC costs (economic) and minimize farmers' perception of economic unfairness (social). Due to the model's centralized nature, the non-dominated solutions with the minimal operation costs of the whole SC offer maximum cost savings. Besides, the model allows a more efficient use of natural resource (e.g., savings in planted area) and a fair solution for farmers, which implies a win-win situation. More specifically, all the model's solutions can recommend to managers the areas that should be planted by each farmer with each crop in each week, and what area should be harvested by each farmer with each crop in each week, and what quantity would be obtained from these harvests, how much of that harvest should be dried in the farmer's dryer and in the central dryer per week, when and in what quantity should previously dried crops be sorted on each farm per crop, how much of each crop should each farmer keep in stock per week, when and in what quantity should each farmer transport each crop to the processor, and therefore, when and in what quantity will crops be delivered to the processor.

The model also provides managers with performance measures of the different obtained plans, such as economic returns per SC member (for each farmer and processor location), economic results broken down for each activity, farmers' land and resource utilization, concentration of the obtained active molecules, or farmers' perception of economic unfairness, which provide processors with relevant information to determine which planning has more potential to be accepted by farmers.

Indeed to implement the model into real SCs, two main requirements should be met. One key requirement for the proposed model's successful use is that all the SC members should be committed to implement the selected plan among all the non-dominated solutions. This could be encouraged by signing contracts in which the processor is committed to purchase the entire harvest obtained by farmers if they respect the selected plan as herein proposed, or adopt another collaborative mechanism, such as signing non exclusivity contracts with farmers so that if there is any unused area left after performing the planned plantation, they can also participate in producing MPs or non-medicinal crops for other processors.

Another important requirement for implementing the model into real life is to have the necessary data to run the model. The required data are related to the unit costs of performing the different MP production and distribution activities, ranging from MPs' behavior (weight change with drying and sorting, plant yields, concentration of active molecules, minimum growth time before harvest) to available resources (available land, drying, sorting, storage capacity) and demand.

Hence one limitation for implementing the model could be that not all processor companies could have studies into the input data on how the concentration of active molecules in the plants behaves according to the plant's growth time and season. The reason for this is that it is assumed that determining the behavior of this concentration of active molecules in plants is externally calculated by precise agronomic functions that may consider other factors, such as temperature, humidity and other weather conditions.

Even for the companies that have the necessary input information available, the model presents a limitation: assuming the concentration of active molecules as being deterministic when it is actually uncertain. It is uncertain because, despite having a very precise agronomic model to predict the concentration of active molecules based on forthcoming weather conditions, real future climate conditions can never certainly be known until future periods become current ones.

To use the model despite this last limitation, the behavior of the concentration of active molecules would have to be updated for new weather conditions with agronomic studies, and the model would have to be rerun with these updated values. If a decision has been made in the SC when a change in the behavior of the concentration of active molecules in plants occurs, the model can be run by forcing the decision variables linked with the decisions already made to be input data and by keeping those decisions that are still pending planning as variables. For example, if the planting of MPs has already taken place, the model can be fed information about the areas that have been planted and during which periods, and can keep the variables related to harvesting, drying, inventory transport, etc., as decisions.

Indeed the model can be run in a rolling horizon scheme either by period (every time a predefined time period elapses) or event (after a success). Every time the model is rerun, its input parameters should be updated and previous decisions made about planting certain land areas with specific plants should be included in the model as constraints by fixing the optimal value corresponding to these variables. If all the planting decisions have been made, the model can be employed to decide about the value of the remaining decision variables, such as when and how much to harvest, using more updated information.

8. Conclusions and future research lines

This paper proposes a conceptual framework to characterize the CPHP problem that is used to review optimization models for this problem and to characterize the problem under study. Most models in the literature are designed for those cases in which fruit are harvested as they ripen (continuous harvest) and are employed for food use. Therefore, gaps are identified, such as modeling discrete plant harvesting or optimizing the concentration of active molecules in plants, among others, which this paper bridges.

The multi-objective mathematical programming model for CPHP herein proposed is validated by its application to the case study of MPs in Basilicata (Italy). Its main novelties are the consideration of plants with a biennial lifes pan and for medicinal purposes, modeling discrete harvests, a minimum time between planting and the first harvest, and also between two consecutive harvests, plant yield dependence and its concentration of active molecules on the plant growth time before harvest, post-harvest activities of MPs (drying and sorting), the transformation of perishable crops into non-perishable ones, the stabilization of their active molecule concentration, the optimization of active molecules in plants, as well as the joint optimization of active molecule concentration, SC costs and economic unfairness among farmers.

The model is solved using the ε-constraint method after verifying that the objectives are not aligned. The analysis of the 13 obtained schedules shows that economic unfairness among farmers can be substantially reduced, while obtaining similar values for costs and the concentration of active molecules in the delivered plants. These results provide processors with relevant information because they can gain by farmers participating in the implementation of centralized planning and, if this unfairness is reduced, with no negative impact on both costs and the concentration of active molecules in the acquired plants. Finally, the TOPSIS method is employed to select the centralized plan to be implemented into the SC. Finally, the main planned decisions related to the selected plan are displayed.

In future research, the proposed model can be extended by modeling the uncertainty that is inherent in MP production, such as uncertain MPs yield, MPs weight reduction when dried, or the proportion of MPs that are discarded during plant sorting. In addition, the production processes performed by the processor can be included in future models.

Data availability

The data that has been used is confidential.

Acknowledgments

We acknowledge the support of Project 691249, RUCAPS: “Enhancing and implementing knowledge based ICT solutions within high risk and uncertain conditions for agriculture production systems”, funded by the European Union’s research and innovation programme H2020 Marie Skłodowska-Curie Actions. We also thank Dr. Domenico Cerbino for his valuable contribution to the biology/cultivation techniques of the MPs, and EVRA srl (www.evraitalia.it) for supporting the MP value chain.

References

[1] A.A. Haile, Important medicinal plants in ethiopia: a review in years 2015–2020, Herbs and Spices - New Processing Technologies, IntechOpen, 2021 [Working Title], doi:10.5772/intechopen.97937.
[2] U. Schippmann, D.J. Leaman, A.B. Cunningham, Impact of Cultivation and Gathering of Medicinal Plants on Biodiversity: Global Trends and Issues, FAO, 2002.
[3] T. van Andel, R. Havinga, Sustainability aspects of commercial medicinal plant harvesting in Suriname, For. Ecol. Manag. 256 (2008) 1540–1545, doi:10.1016/j.foreco.2008.06.031.
[4] A.W. Burger, Crop classification, Physiologic Basis Crop Growth Development, 1984, pp. 1–12, doi:10.2135/1984.physiologicalbasis.c1.
[5] A. Balasubramanian, Classification of Agricultural Crops, 2014.
[6] O. Ahumada, J.R. Villalobos, A tactical model for planning the production and distribution of fresh produce, Ann. Oper. Res. 190 (2011) 339–358, doi:10.1007/s10479-009-0614-4.
[7] O. Ahumada, J.R. Villalobos, Operational model for planning the harvest and distribution of perishable agricultural products, Int. J. Prod. Econ. 133 (2011) 677–687, doi:10.1016/j.ijpe.2011.05.015.
[8] J. Han, N. Lin, J. Ruan, X. Wang, W. Wei, H. Lu, A model for joint planning of production and distribution of fresh produce in agricultural internet of things, IEEE Internet Things J. (2020) 1 –1, doi:10.1109/JIOT.2020.3037729.
[9] M.M.E. Alemany, A. Esteso, Á. Ortiz, M. del Pino, Centralized and distributed optimization models for the multi-farmer crop planning problem under uncertainty: application to a fresh tomato Argentinean supply chain case study, Comput. Ind. Eng. 153 (2021) 107048, doi:10.1016/j.cie.2020.107048.
[10] A. Esteso, M.M.E. Alemany, Á. Ortiz, Impact of product perishability on agri-food supply chains design, Appl. Math. Model. 96 (2021) 20–38, doi:10.1016/j.apm.2021.02.027.
[11] A. Esteso, M.M.E. Alemany, A. Ortiz, S. Liu, Optimization model to support sustainable crop planning for reducing unfairness among farmers, Cent. Eur. J. Oper. Res. (2021), doi:10.1007/s10100-021-00751-8.
[12] I. Fikry, M. Gheith, A. Eltawil, An integrated production-logistics-crop rotation planning model for sugar beet supply chains, Comput. Ind. Eng. 157 (2021) 107300, doi:10.1016/j.cie.2021.107300.
[13] A. Hajimirzajan, M. Vahdat, A. Sadegheih, E. Shadkam, H. El Bilali, An integrated strategic framework for large-scale crop planning: sustainable climate-smart crop planning and agri-food supply chain management, Sustain. Prod. Consum. 26 (2021) 709–732, doi:10.1016/j.spc.2020.12.016.
[14] O. Ahumada, J.R. Villalobos, A.N. Mason, Tactical planning of the production and distribution of fresh agricultural products under uncertainty, Agric. Syst. 112 (2012) 17–26, doi:10.1016/j.agsy.2012.06.002.
[15] A.M. Costa, L.M.R. dos Santos, D.J. Alem, R.H.S. Santos, Sustainable vegetable crop supply problem with perishable stocks, Ann. Oper. Res. 219 (2014) 265–283, doi:10.1007/s10479-010-0830-y.
[16] A.N. Mason, J.R. Villalobos, Coordination of perishable crop production using auction mechanisms, Agric. Syst. 138 (2015) 18–30, doi:10.1016/j.agsy.2015.04.008.
[17] H. Flores, J.R. Villalobos, A modeling framework for the strategic design of local fresh-food systems, Agric. Syst. 161 (2018) 1–15, doi:10.1016/j.agsy.2017.12.001.
[18] H. Flores, J.R. Villalobos, O. Ahumada, M. Uchanski, C. Meneses, O. Sanchez, Use of supply chain planning tools for efficiently placing small farmers into high-value, vegetable markets, Comput. Electron. Agric. 157 (2019) 205–217, doi:10.1016/j.compag.2018.12.050.
[19] M.M. Najafabadi, S. Ziaee, A. Nikouei, M. Ahmadpour Borazjani, Mathematical programming model (MMP) for optimization of regional cropping patterns decisions: a case study, Agric. Syst. 173 (2019) 218–232, doi:10.1016/j.agsy.2019.02.006.
[20] J. Jonkman, A.P. Barbosa-Póvoa, J.M. Bloemhof, Integrating harvesting decisions in the design of agro-food supply chains, Eur. J. Oper. Res. 276 (2019) 247–258, doi:10.1016/j.ejor.2018.12.024.
[21] S.A. Jifroudi, E. Teimoury, F. Barzinpour, Designing and planning a rice supply chain: a case study for Iran farmlands, Decis. Sci. Lett. (2020) 163–180, doi:10.5267/j.dsl.2020.1.001.
[22] L.P. Catalá, G.A. Durand, A.M. Blanco, J.A. Bandoni, Mathematical model for strategic planning optimization in the pome fruit industry, Agric. Syst. 115 (2013) 63–71, doi:10.1016/j.agsy.2012.09.010.
[23] T.D. Nguyen, U. Venkatadri, T. Nguyen-Quang, C. Diallo, M. Adams, Optimization model for fresh fruit supply chains: case-study of dragon fruit in Vietnam, AgriEngineering 2 (2019) 1–26, doi:10.3390/agriengineering2010001.
[24] K. Darby-Dowman, S. Barker, E. Audsley, D. Parsons, A two-stage stochastic programming with recourse model for determining robust planting plans in horticulture, J. Oper. Res. Soc. 51 (2000) 83–89, doi:10.1057/palgrave.jors.2600858.
[25] B. Adenso-Díaz, G. Villa, Crop planning in synchronized crop-demand scenarios: a biobjective optimization formulation, Horticulturae 7 (2021) 347, doi:10.3390/horticulturae7100347.
[26] C. Costa, F. Antonucci, F. Pallottino, J. Aguzzi, D. Sarriá, P. Menesatti, A review on agri-food supply chain traceability by means of RFID technology, Food Bioprocess Technol. 6 (2013) 353–366, doi:10.1007/s11947-012-0958-7.
[27] O. Ahumada, J. Rene Villalobos, A. Nicholas Mason, Tactical planning of the production and distribution of fresh agricultural products under uncertainty, Agric. Syst. 112 (2012) 17–26, doi:10.1016/j.agsy.2012.06.002.
[28] A.N. Mason, J.R. Villalobos, Coordination of perishable crop production using auction mechanisms, Agric. Syst. 138 (2015) 18–30, doi:10.1016/j.agsy.2015.04.008.
[29] I. Khan, A. Zakari, M. Ahmad, M. Irfan, F. Hou, Linking energy transitions, energy consumption, and environmental sustainability in OECD countries, Gondwana Res. 103 (2022) 445–457, doi:10.1016/j.gr.2021.10.026.
[30] G. Mavrotas, Effective implementation of the ε-constraint method in multi-objective mathematical programming problems, Appl. Math. Comput. 213 (2009) 455–465, doi:10.1016/j.amc.2009.03.037.
[31] C.L. Hwang, A.S.M. Masud, Methods for multiple objective decision making, Multiple Object Decision Making - Methods Applications (1979) 21–283.