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Investigating the Potential Effects of Food Waste Reduction Interventions Within the Leafy Vegetable Supply Chain in Kermanshah Province, Iran

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Abstract: Despite the increasing concerns regarding meeting the world's future food demand, there is still a substantial quantity of food loss and waste (FLW), particularly concerning fruits and vegetables. In the case of Kermanshah province, inefficiencies within the leafy vegetable supply chpain (LVSC) contribute to an alarming annual waste of 39% of leafy vegetables. Although several studies have proposed strategies and recommendations for mitigating this waste, the actual impact of these interventions on reducing FLW has not been thoroughly examined or quantified. Using System Dynamic Modeling, this study offers a novel approach to quantify the impact of interventions on waste reduction. The quantification results reveal four key interventions reducing vegetable waste at the production stage: biotic (31.2%) and abiotic stress control (14.4%), improved educational services (23.2%), and access to quality inputs (15.2%). Furthermore, the results suggest that early-stage factors in the LVSC play a crucial role in determining waste accumulation in later stages. Improvements in packaging facilities and cold supply chain infrastructure, along with better coordination and information sharing among stakeholders at the market stage, significantly help reduce waste. Additionally, effective planning for household food shopping is emphasized as a crucial strategy for minimizing waste at the consumption stage. This holistic approach focuses on the interconnectedness of actions across various stages of the supply chain and their combined effect on decreasing the overall waste of leafy vegetables.

Keywords: food loss and waste; leafy vegetable supply chain; waste reduction interventions; system dynamic modeling; Kermanshah

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1. Introduction

Today, population expansion, combined with natural limits such as natural disasters, climate change, and water scarcity, poses a significant threat to the world's food security [1]. Despite these concerns, one-third of the food produced worldwide is wasted or lost annually, and fruits and vegetables account for 66% of its mass [2,3]. When defining food loss and waste (FLW), both food loss and waste are considered. Food loss refers to the decrease in the quantity of consumable food across the stages of production, post-harvest, and processing within the food supply chain (FSC) and is more prevalent in underdeveloped countries. On the other hand, food waste refers to the discarding of consumable food at the consumer and retail stages, mainly in developed countries. This wastage of food has significant environmental consequences and represents a missed chance to enhance food security [4]. According to statistics, Iran contributes to 2.7 percent of the global FLW (35 million tonnes per year) [5]. This ongoing trend of FLW puts additional strain on the agricultural sector and results in the squandering of precious production resources such as land, water, and other resources, along with more emissions of greenhouse gases [4,6]. Iran's agriculture industry, as the primary source of food for the country, is currently facing a limited supply of production resources [7,8]. At the same time, future projections indicate that Iran's population will reach 95 million by 2050 [9], necessitating the production of at least an additional 25 million tones of agricultural products [10]. To ensure a long-term food supply and attain food security goals, any reduction in FLW means returning a significant amount of food to the consumption cycle without placing excessive strain on the agricultural sector [11].

Nevertheless, FLW remains extremely high in Iran, where vegetables have the highest rate of agricultural FLW (42%) [12]. In Kermanshah, a major agricultural hub in Iran, significant annual waste of leafy vegetables results from supply chain (SC) inefficiencies, including perishability, production challenges, inadequate marketing infrastructure, and poor consumer management [13,14]. Given population growth and related challenges, addressing FLW and implementing effective interventions is crucial. Recent research has mostly focused on managing FLW and its environmental and economic impacts rather than prevention. Some notable approaches in this regard include a life-cycle assessment [15], cost—-benefit analysis [16], and multi-objective optimization methods [17]. Despite offering strategies for waste reduction, these studies have not thoroughly examined or quantified the specific impact of interventions on FLW [18]. To address this gap, this study aims to create a framework using System Dynamic Modeling (SDM) to assess the effectiveness of interventions in reducing waste in the leafy vegetable supply chain (LVSC) in the Kermanshah province. Leafy vegetables are categorized as green vegetables and include celery, spinach, leeks, mint, parsley, watercress, and coriander, which are commonly consumed in Iran as the main meal (cooked) and dessert. As lettuce and cabbage have distinct SCs compared to other green vegetables, they were not incorporated in this research study. To achieve its main goal, this research addresses four questions: (1) How is Kermanshah's LVSC structured, and which areas should waste reduction interventions (WRIs) target? (2) What are the main factors influencing waste in each LVSC area? (3) Which WRIs are most significant? (4) How much waste do they reduce? The study covers leafy vegetable loss and waste from pre-harvest to consumption, using "leafy vegetable waste (LVW)" to describe discarded food.

The novelty of this study lies in its development of a framework using SDM to evaluate the impact of waste reduction interventions (WRIs) across the food supply chain (LVSC). While the application of SDM has been explored in food waste studies, such as modeling food waste behavior at the household level, this research distinguishes itself by employing SDM to holistically assess the efficiency and impact of WRIs across multiple stages of the food supply chain, addressing key challenges like stakeholder interaction and waste generation mechanisms.

2. Literature Review

The literature review is structured in two sections. The first section consists of studies specifically focusing on LVW. The second section reviews studies on waste reduction interventions and causes of waste within fresh FSC.

2.1. Leafy Vegetable Waste

Studies on FLW, specifically in LVSC, are scarce in the literature. Most of the studies on FLW refer to general FLW and discuss waste in fruit and vegetable chains more often [2,18,19]. A literature search on specific LVW has resulted in a few studies, which are summarized below. A study in Brazil found that leafy vegetable losses in retail chains varied significantly, ranging from 1% to 97%, depending on the vegetable species, suppliers, and stores. The primary causes were poor handling, marketing practices, and the initial quality of the products received [20]. In a study by Ref. [21] on African leafy vegetables, key barriers to their production, processing, marketing, and consumption were identified as a lack of improved germplasm, absence of a seed supply system, reliance on traditional processing methods, and the dominance of informal markets. Two years later, Elolu, et al. [22] noted that post-harvest losses in African leafy vegetables exceeded 50% and stressed the need for better post-harvest processing to reduce waste. Moradi, et al. [14] highlighted the importance of developing processing industries to minimize waste in the LVSC. Garavito [23] found that unfair business practices and a lack of policies were major contributors to FLW in Brazilian leafy vegetables. These studies offer valuable insights into managing LVSC and emphasize the need for better handling practices and waste management, yet the specific impact of these interventions on reducing FLW remains inadequately examined and quantified.

2.2. Waste Reduction Interventions

WRIs encompass various actions and modifications implemented within the food system to specifically minimize waste throughout the SC. They include operational and infrastructural adjustments, and efforts focused on changing human behavior [24]. Understanding the underlying causes is essential before assessing the outcomes of WRIs. Recent studies have identified several effective strategies for reducing FLW across the FSC. For instance, Johnson, et al. [25] demonstrated that adjusting harvest times according to market demand forecasts can greatly reduce waste at the farm level. Additionally, Lawal, et al. [26] found that educating farmers on the best practices for post-harvest handling, storage, and transportation of agricultural produce can lead to substantial reductions in spoilage. At the market level, research has emphasized the importance of improved communication and coordination among stakeholders in the SC to better align production with market needs. Birkmaier, et al. [27] and Urugo, et al. [6] indicated that collaborative platforms connecting farmers directly with retailers can reduce overproduction by ensuring that supply more accurately meets demand. Furthermore, advancements in inventory management systems have enabled retailers to track perishable items more effectively, facilitating timely discounts and promotions before expiration dates [6,28]. At the consumer level, digital tools such as mobile apps designed to track food inventory have shown to be effective in significantly reducing waste. Porat, et al. [2] noted that mobile applications alert consumers when food expiration dates are approaching, helping them manage their purchases more effectively. Moreover, educational campaigns aimed at raising consumer awareness about food waste have proven effectiveness in promoting practices such as meal planning and proper food storage techniques [6,29]. Identifying the causes of food waste is essential for formulating effective strategies aimed at its reduction. A literature review reveals that waste drivers and causes vary across countries and stages of the fresh FSC [30]. Furthermore, given the short shelf life of the products and ongoing contact with various FSC stakeholders, the origins of waste at one stage may also be hidden at a later level [19]. A comprehensive analysis of previous research indicates significant gaps in knowledge, including a limited number of FLW studies in emerging economies [31]. Moreover, the majority of previous research has concentrated on a specific chain stage [32,33]. Thus, addressing FLW effectively requires a thorough SC investigation and the use of multidimensional techniques to map connections between FLW causes at various stages [34]. Additionally, using techniques such as structural interpretive modeling (ISM) [34,35] and a decision-making trial and evaluation laboratory (DEMATEL), some researchers investigated the determinants of FLW and suggested promising measures to reduce it without estimating the potential impact [36]. The fact that the conclusions are based on expert opinion rather than real data is one of the limits of these methodologies, even though they give an overview of the most significant elements impacting FLW and ways for lowering it. Another shortcoming of past studies is the lack of measurements of the volume and location of the FLW, which restricts the provision of any solutions [37]. While not sufficient, several studies have assessed the effectiveness of proposed waste reduction strategies [18]. Magalhães, et al. [18] recently presented a hybrid SWARA-fuzzy WASPAS approach for assessing waste reduction strategies for fruits and vegetables in Portugal. A key weakness of this study is its reliance on expert judgment without quantifying the impact of waste-reduction interventions. Table 1 provides an overview of the studies on FLW's causes. This section identifies FLW causes in fresh FSC based on data from various articles. These causes are explained in greater detail in the following section.

Table 1. A selection of studies on the causes of waste within the fresh FSC.

Source	Method	SC Stage					Product
		H	FS	Pro	M	P	
[38]	Review	✓	✓	✓	✓	✓	Plant production
[39]	Ethnographic	✓					Food
[40]	Secondary data		✓		✓	✓	Plant production
[37]	Review			✓	✓	✓	Food
[41]	Weight FLW				✓		Fruit and vegetables
[42]	Review				✓	✓	Fruit and vegetables
[43]	Review				✓	✓	Fruit and vegetables
[44]	Multi-level analysis	✓					Food
[45]	Weight FLW	✓					Food
[46]	TPB	✓					Fruit and vegetables
[47]	Interview	✓	✓	✓	✓	✓	Food
[48]	Review	✓	✓	✓	✓	✓	Food
[49]	Qualitative study			✓			Food
[50]	Fuzzy MICMAC and TISM			✓	✓	✓	Perishable foods
[51]	Review	✓	✓	✓	✓	✓	Food
[52]	Review				✓	✓	Tomato
[53]	Review	✓					Food
[54]	Materials flow analysis		✓				Food
[33]	Review				✓		Food
[55]	Explorative study				✓		Food
[32]	Qualitative study					✓	Horticulture
[35]	ISM			✓	✓		Fruit and vegetables
[36]	DEMATEL			✓	✓	✓	Fruit and vegetables
[56]	Qualitative study				✓	✓	Horticulture
[57]	Qualitative study			✓	✓	✓	Food
[2]	Review	✓			✓		Fruit and vegetables
[58]	Qualitative study		✓				Food
[59]	Qualitative study					✓	Organic food
[60]	Case study				✓	✓	Fruit and vegetables
[61]	Review		✓				Food
[62]	Qualitative content analysis		✓				Food
[63]	Commodity System Assessment				✓	✓	Tomato
[64]	Quantitative method					✓	Fruit
[34]	ISM				✓	✓	Fruit and vegetables
[21]	Review	✓		✓	✓	✓	African leafy vegetables
[65]	qualitative research techniques					✓	Fruit
[14]	SDM	✓	✓	✓	✓	✓	Leafy vegetables
[22]	Review			✓	✓		African indigenous vegetables
[23]	Qualitative study				✓	✓	Leafy vegetables
[20]	Quantitative method				✓		Leafy vegetables

Note: P—Production; M—Marketing; Pro—Processing; FS—Food services; C—Consumption; FLW—Food loss and waste; TPB—Theory of planning behavior; TISM—Total Interpretive Structural Modelling; ISM—Interpretive Structural Modelling; DEMATEL—Decision-Making Trial and Evaluation Laboratory; SDM—System Dynamic Modeling.

3. Materials and Methods

3.1. The Study Area and Products

The research was conducted in Kermanshah, a province in western Iran with a population of approximately 2 million (1,952,434 people) residents and an area of 25,045.4 square kilometers (see Figure 1) [66]. This region has one of the largest amounts of waste from green vegetables [14]. Within the research region, there are between 800 and 1000 hectares of annual leafy vegetable cultivation, with each hectare yielding about 65 tones of crop annually. The LVSC of all those products consists of four key stages: production (farmers), marketing (retailers and wholesalers), processing (processors), and consumption (food services and households).

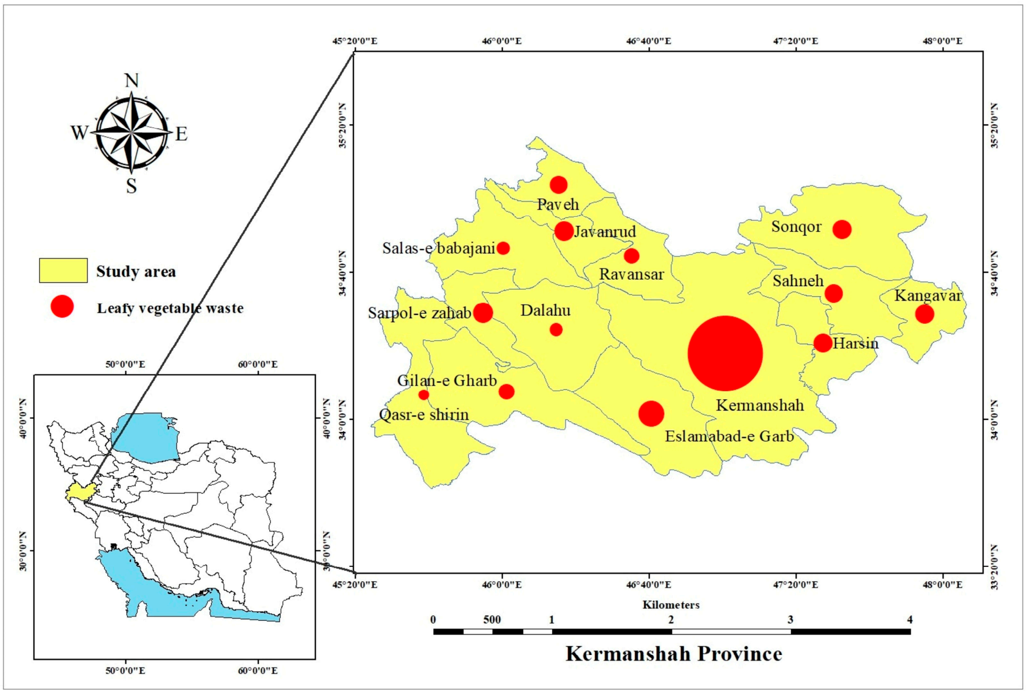

Figure 1. A map of the research area.

3.2. Data

The primary data collection tool was a questionnaire. The information regarding how the questionnaire was developed, along with examples of questions, can be found in Appendix A. The statistical population was subdivided into two groups: the primary group was composed of local and national subject matter experts (academic specialists, specialists from agricultural research institutes, and experts from the Ministry of Agriculture working in the Kermanshah province) and stakeholders with a research or executive background related to the research topic. This group was surveyed to learn their opinions on the following topics: (1) evaluating the quality of the questionnaire (5 participants), (2) defining the structure of LVSC (1st focus group discussion (FGD), (3) choosing the reasons why leafy vegetables end up in waste (12 participants), and (4) weighing the waste causes (60 participants). The second group consisted of a variety of LVSC stakeholders, including farmers, marketing and processing stakeholders, chefs working in the food industry, and Kermanshah province housewives who are in charge of cooking at the household level. The samples were selected for the household and production level using a proportional stratified random sampling method. The sample size was calculated in these phases using Cochran's formula [67]. For the other statistical groups, a full census was conducted. In total, 728 samples were selected and studied (172 farmers, 83 wholesalers and retailers, 16 processing units, 384 households, and 73 food services). These data were used to determine the current condition of the waste causes and to measure the amount of LVW and leafy vegetables flowing into the LVSC. Additionally, based on United Nations forecasts of Iran's population, future population figures and trends were estimated [68].

3.3. Analytical Process and Method

This study employed a quantitative research design utilizing SDM to evaluate the potential impacts of WRIs within the LVSC in Kermanshah province, Iran. The procedures shown in Figure 2 were chosen as the major approach to the study.

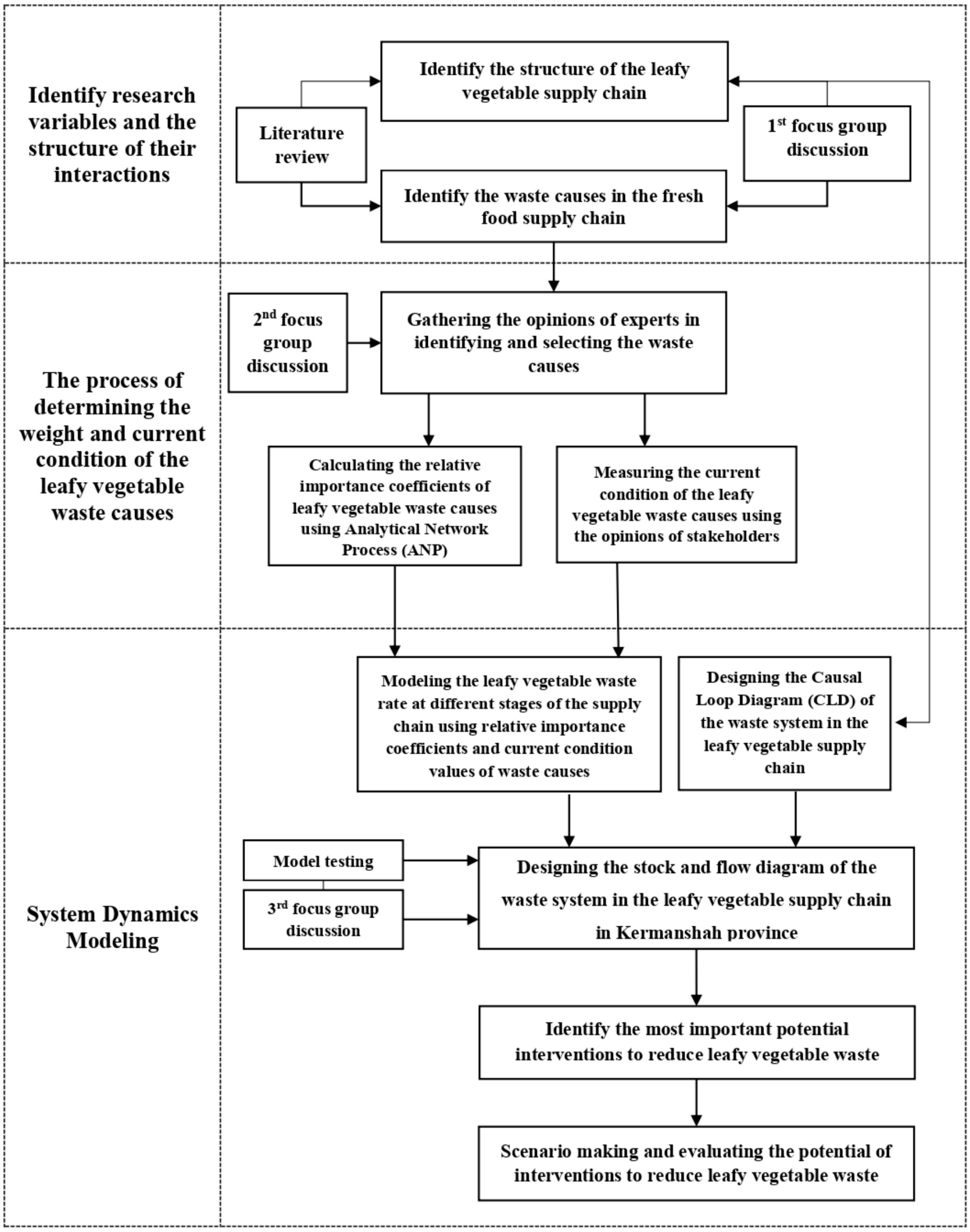

Figure 2. The procedure of the study.

3.3.1. Guidance to Reader on Steps of the Study

The presentation of SDM is rather complex as it involves multiple sequential stages. To simplify the complexity of the presentation of the model, we have divided the complex process of SDM into several steps. Below, we outline the first three initial steps. The third step, which focuses on the SDM of waste within the LVSC, includes further sequential steps detailed in Section 3.3.2, with an explanation of the steps taken in modeling the waste rate at each stage of LVSC in Section 3.3.3. This sub-section concludes Section 3.4 with a simulation of the model to test the scenarios.

1. Identifying research variables and the structure of their interactions

Initially, an extensive review of the literature and interaction with LVSC experts and stakeholders was conducted using the FGD technique [69]. This procedure led to the development of the LVSC structure and a comprehensive list of waste factors.

2. The process of determining the weight and current condition of the causes of LVW

To assess LVW causes' impact on waste, relative importance coefficients (RICs) and current condition values (CCVs) were collected. The sum of multiplying these variables provides a quantitative method to evaluate the impact of different waste reduction interventions in the model. To measure the RICs that cause LVW, the analytical network process (ANP) was applied. This approach, which is an expanded version of the hierarchical analysis approach, is used to rank criteria based on pairwise comparisons [70]. This approach allows for the consideration of the interactions between the LVW causes at each level. Actor perceptions and a Likert scale were also used to measure the CCVs of LVW causes.

3. System dynamics modeling of waste within the LVSC

SDM offers a comprehensive understanding of complex systems by capturing their interdependence, interaction, information feedback, and circular causation over time [71]. This method provides a full view of the real world by combining feedback between system variables. The LVSC's waste system was designed using the SDM and the procedures listed below [72]. To explain this model, several additional steps are necessary. These steps are presented in Section 3.3.2 below.

3.3.2. Steps in SDM

(a) Problem statement

The dimensions of the research problem and dynamic problem structure must first be defined and examined in SDM. In socioeconomic research, two aspects—the goal of the study and the significance of different factors on the elements thought to be within the borders of a system—define the boundaries of a system [72]. The main purpose of this research was to model the waste system within the LVSC in Kermanshah province.

(b) Designing a conceptual model

Dynamic hypotheses were developed to design the causal loops in this section after the research subject, the system structure, the system boundary, and the research variables were established. The causative structure of waste inside the LVSC is depicted in Figure 3. This model presents the characteristics and determinants of the inflow and outflow of products inside the LVSC.

(c) Formulation of the simulation model

After the system has been conceptualized, a stock and flow diagram must be developed (Figure 4). The process of quantifying the model involves the following steps:

- Identifying input parameters: Input parameters are those that are not computed by the model but are given as inputs for the model to calculate the remaining parameters. Table 2 provides an overview of the model inputs.
- Definition of mathematical relationships for the remaining parameters: In an SDM, many model parameters are estimated through mathematical equations. Table 3 presents the mathematical formulas for estimating the main parameters of the model.

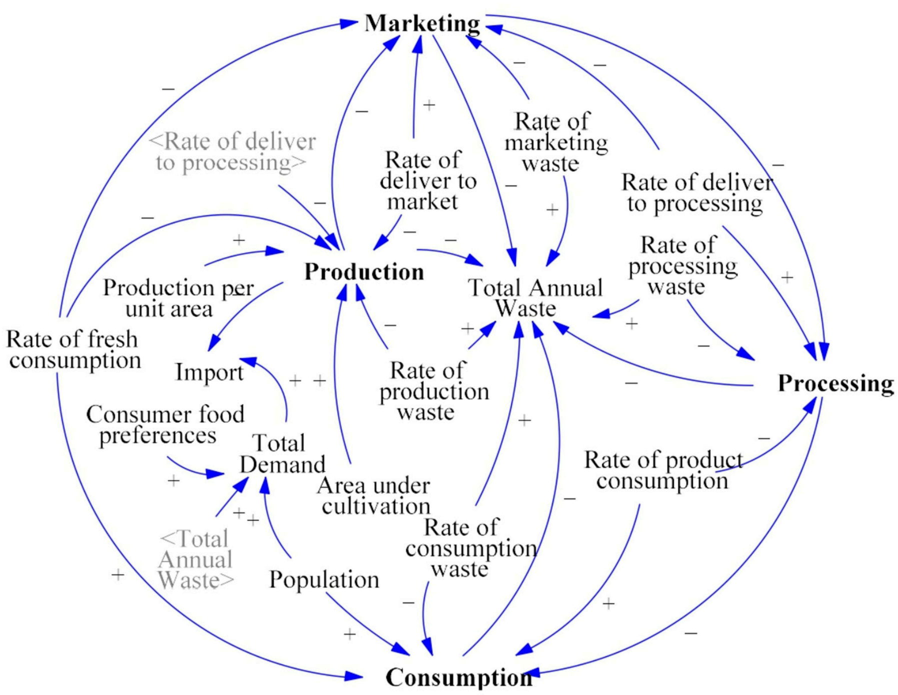

Figure 3. Causal loop diagram of a waste system within the leafy vegetable supply chain [14]. Note: (+)—Strengthening; (−)—Weakening.

Table 2. Initial values of waste system variables in the leafy vegetable supply chain.

Subsystems	Variables		Initial Values	Units
Demand subsystem	Population (Po)		2.070	Person
	Per capita leafy vegetable consumption (PLVC)		24	kg
Production subsystem	Area under cultivation		800	Ha
	Production per unit area		65,000	kg
	Annual production of leafy vegetables		52,000,000	kg/year
	Rate of delivery from production to household (DPH)		25	%
	Rate of delivery from production to processing (DPPro)		4	%
	Rate of delivery from production to market (DPM)		47	%
	Rate of production waste		24	%
Marketing subsystem	Import volume (IV)		28,492,000	kg/year
	Rate of delivery from production to market (DPM)		47	%
	Rate of delivery from market to household (DMH)		84.5	%
	Rate of delivery from market to processing (DMPro)		1.5	%
	Rate of delivery from market to food services (DMFS)		3	%
	Rate of marketing waste		11	%
Processing subsystem	Rate of delivery from production to processing (DPPro)		4	%
	Rate of delivery from market to processing (DMPro)		1.5	%
	Rate of delivery from processing to consumption (DProC)		93.5	%
	Rate of processing waste		6.5	%
Consumption subsystem	Rate of delivery from production to consumption (DPC)		25	%
	Rate of delivery from market to consumption (DMC)		84.5	%
	Rate of delivery from market to food services (DMFS)		3	%
	Rate of delivery from processing to consumption (DProC)		93.5	%
	Annual consumption (AC)		48,740,000	kg/year
	Rate of consumption waste	Rate of household waste	21	%
		Rate of food services waste	18	%
		Rate of processed consumption waste	5	%

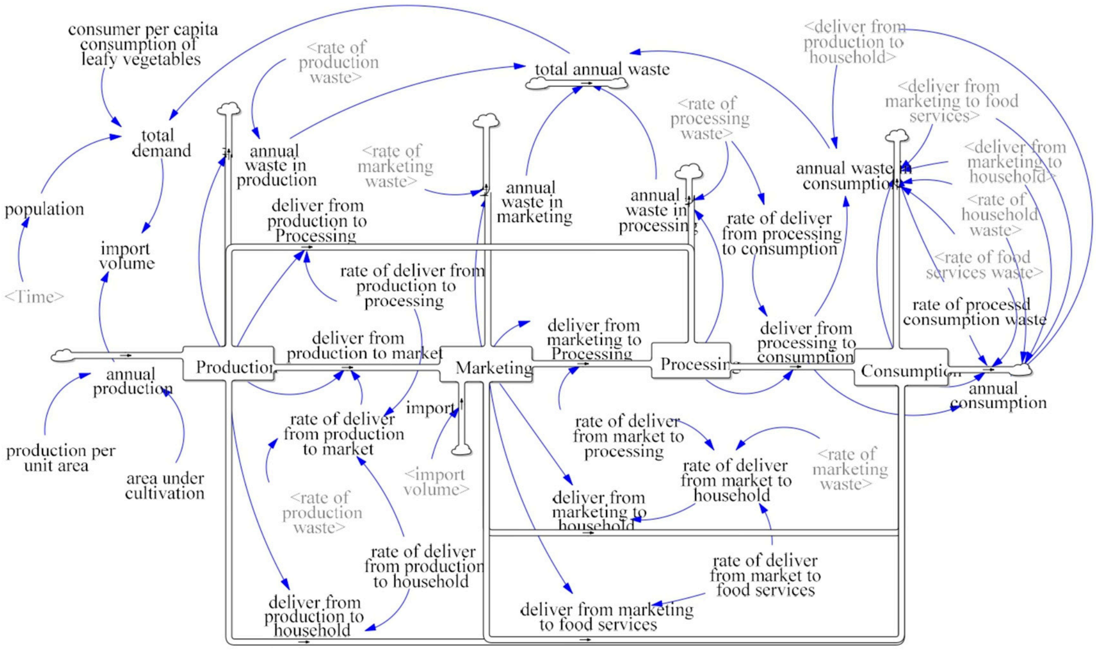

Figure 4. Stock and flow diagram of the waste system in the leafy vegetable supply chain [14].

Table 3. Mathematical equations of some of the important parameters of the leafy vegetable supply chain model.

Variables	Formula	Units
Total demand (TD)	TD =(Po × PLVC)+Total annual waste	kg/year
Import volume (IV)	IV = TD + AP	kg/year
Annual production (AP)	AP = Area under cultivation + Production per unit area	kg/year
Cumulative production (CP)	$\mathrm{CP} = \int_{t_0}^{t} \mathrm{AP} - (\mathrm{APW} + \mathrm{SPH} + \mathrm{SPPro} + \mathrm{SPM})$	kg/year
Annual waste in production (AWP)	AWP = Cumulative production × Rate of production waste	kg/year
Cumulative marketing (CM)	$\mathrm{CM} = \int_{t_0}^{t} (\mathrm{I} + \mathrm{DPM}) - (\mathrm{DMH} + \mathrm{DMFS} + \mathrm{DMPro} + \mathrm{AWM})$	kg/year
Annual waste in marketing (AWM)	AWM = CM × Rate of marketing waste	kg/year
Cumulative processing (CPro)	$\mathrm{CPro} = \int_{t_0}^{t} (\mathrm{DPPro} + \mathrm{DMPro}) - (\mathrm{DProC} + \mathrm{AWPro})$	kg/year
Annual waste in processing (AWPro)	AWPro = CPro × Rate of processing waste	kg/year
Cumulative consumption (CC)	$\mathrm{CC} = \int_{t_0}^{t} (\mathrm{DPC} + \mathrm{DMC} + \mathrm{DMFS} + \mathrm{DProC}) - (\mathrm{AC} + \mathrm{AWC})$	kg/year
Annual waste in consumption (AWC)	AWC = CC × Rate of consumption waste	kg/year

Note: The concept of each symbol is presented in Table 2.

3.3.3. Modeling the Rate of Annual Waste at Each Stage of LVSC

To facilitate the evaluation of various measures and strategies targeting waste reduction at different stages of the LVSC, the waste rates in each stage were modeled based on the RICs derived from ANP and the CCVs of the variables.

(a) Modeling the rate of annual production waste

Based on survey results, it was found that 24% of yearly production waste occurs. The RICs of waste causes in the production stage (RICPs) resulting from ANP and CCVs of these variables (CCVPs) were used to model the rate of annual production waste and enable the implementation of various interventions and policies on the reduction in waste in this stage (Equation (1), Table 4 and Figure 5).

$$\text{Rate of production waste} = \sum_{1}^{n} \text{RICPs} \times \text{CCVPs} \tag{1}$$

Unit: 1/Year

Table 4. Weights of waste causes.

Stages	Variables	RICs	CCVs	Final Weight	CR
Production	Inadequate access to educational and extension services *	0.066	0.863	0.057	0.090
	Pests and diseases *	0.061	0.747	0.046	
	Inadequate access to high-quality inputs such as seeds and fertilizer. *	0.081	0.457	0.037	
	Abiotic stresses include water, temperature, and nutritional stress *	0.069	0.512	0.035	
	Inadequate weed management *	0.043	0.701	0.030	
	Improper farm harvesting and handling techniques	0.027	0.588	0.016	
	Lack of proper storage facilities	0.015	0.734	0.011	
	Production exceeds the market demand	0.022	0.235	0.005	
	Severe fluctuations in product prices	0.011	0.254	0.003	
Marketing	Lack of proper packaging facilities *	0.044	0.740	0.032	0.073
	Inappropriate quality of products supplied to market *	0.036	0.612	0.022	
	Inadequate coordination and information sharing among stakeholders *	0.023	0.730	0.017	
	Short shelf life of the product *	0.017	0.679	0.012	
	Poor demand forecasting *	0.017	0.598	0.010	
	Inadequate access to storage facilities	0.011	0.492	0.006	
	Inadequate store management	0.015	0.325	0.005	
	Inadequate transportation and distribution facilities	0.007	0.570	0.004	
	Improper handling in the market	0.006	0.377	0.002	
Processing	Inappropriate quality of products supplied to processing *	0.041	0.750	0.031	0.051
	Inadequate availability of new processing facilities and technologies *	0.044	0.529	0.023	
	Inefficient packaging of processed products	0.013	0.363	0.005	
	Improper processing methods (human error)	0.008	0.413	0.003	
	Insufficient storage facilities for the processed products	0.007	0.413	0.003	
Household	Inappropriate quality of products supplied to households *	0.090	0.848	0.076	0.093
	Inadequate pre-purchase planning *	0.076	0.535	0.041	
	Over-purchasing *	0.050	0.651	0.033	
	Excessive food preparation *	0.037	0.544	0.020	
	Poor food preparation skills	0.040	0.397	0.016	
	Inappropriate food consumption habits	0.027	0.442	0.012	
	Not consuming leftovers	0.020	0.466	0.009	
	Improper food storage management	0.012	0.263	0.003	
Food services	Inappropriate quality of products supplied to food services *	0.098	0.758	0.074	0.090
	Inappropriate food consumption patterns *	0.061	0.733	0.045	
	Inefficient restaurant food management *	0.034	0.442	0.015	
	Inadequate storage facilities and technology *	0.046	0.247	0.011	
	Non-compliance with food quality standards	0.017	0.653	0.011	
	Poor forecasting of food demand	0.016	0.589	0.009	
	Inadequate food preparation skills	0.036	0.234	0.008	
	Not providing customer packaging services for excess food	0.009	0.694	0.006	

Note: *—The most significant waste causes based on the Pareto principle; CR—Consistency Ratio (Optimal: CR $\leq 0/1$); RICs—relative importance coefficients; CCVs—current condition values.

(b) Modeling the rate of annual marketing waste

The rate of annual marketing waste was calculated to be 11%. The marketing stage was modeled using RICs of waste causes (RICMs) and CCVs of these variables (CCVMs), similar to the production stage (Equation (2), Table 4, and Figure 5).

$$\text{Rate of marketing waste} = \sum_{1}^{n} \text{RICMs} \times \text{CCVMs} \tag{2}$$

Unit: 1/Year

(c) Modeling the rate of annual processing waste

Based on questionnaire responses, it was determined that the annual waste rate at this point was 6.5%. Similar to the other sectors, it was modeled using RICs of waste causes in the processing stage (RICPros) and CCVs of these variables (CCVPros) (Equation (3), Table 4, and Figure 5).

$$\text{Rate of processing waste} = \sum_{1}^{n} \text{RICPros} \times \text{CCVPros} \quad (3)$$

Unit: 1/Year

(d) Modeling the rate of annual household waste

Household waste, food service waste, and processed consumption waste are all included in consumption waste. Based on survey results, it was determined that 21% of annual waste is in the household stage. Similar to the earlier stages, the CCVs of these variables (CCVHs) and the RICs of the waste causes in this stage (RICHs) were used to model the rate of its waste (Equation (4), Table 4, and Figure 5).

$$\text{Rate of household waste} = \sum_{1}^{n} \text{RICHs} \times \text{CCVHs} \quad (4)$$

Unit: 1/Year

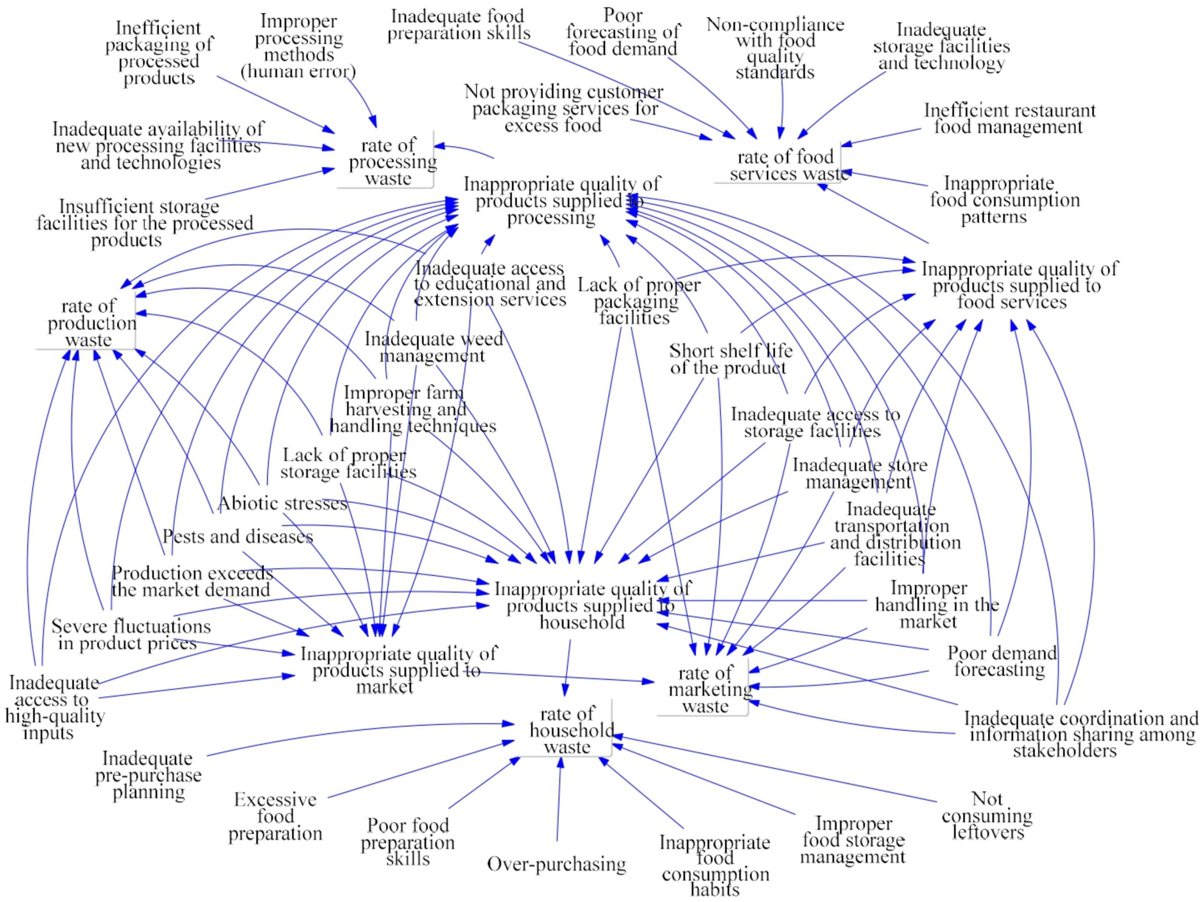

Figure 5. Stock and flow diagram of the waste causes in various stages of the leafy vegetable supply chain.

(e) Modeling the rate of annual food service waste

The findings show that 18% of yearly waste occurred at food service places. The RICs of the waste caused by food services (RICFSs) and the CCVs of these variables (CCVFSs) were also used to estimate the ACW rate of waste at this stage (Equation (5), Table 4, and Figure 5).

$$\text{Rate of food services waste} = \sum_{1}^{n} \text{CCVFSs} \times \text{RICFSs} \tag{5}$$

Unit: 1/Year

(f) Modeling the quality of products supplied to stages

The quality of leafy vegetables provided to the market, processing facilities, household consumption, and food services all contributed to waste. The RICs and CCVs of the waste causes in the earlier stages were used to model the current condition of the product quality supplied to these stages, making it feasible to assess the potential impact of WRIs in the initial stages of LVSC on the quantity of waste in the subsequent stages (Equations (6)–(9)). In the processing and household stages, the weight of these variables will be calculated based on the proportionate volume of leafy vegetables entering from the source stages (Equations (7) and (8) and Figure 5).

$$\text{Inappropriate quality of products supplied to market} = \sum_{1}^{n} \text{RICPs} \times \text{CCVPs} \tag{6}$$

$$\text{Inappropriate quality of products supplied to processing} = \left(\left(\frac{\text{DPPro}}{\text{DPPro} + \text{DMPro}}\right) \times \sum_{1}^{n} \text{RICPs} \times \text{CCVPs}\right) + \left(\left(\frac{\text{DMPro}}{\text{DMPro} + \text{DPPro}}\right) \times \sum_{1}^{n} \text{RICMs} \times \text{CCVMs}\right) \tag{7}$$

$$\text{Inappropriate quality of products supplied to households} = \left(\left(\frac{\text{DPH}}{\text{DPH} + \text{DMH} + \text{DProC}}\right) \times \sum_{1}^{n} \text{RICPs} \times \text{CCVPs}\right) + \left(\left(\frac{\text{DMH}}{\text{DMH} + \text{DPH} + \text{DProC}}\right) \times \sum_{1}^{n} \text{RICMs} \times \text{CCVMs}\right) \tag{8}$$

$$\text{Inappropriate quality of products supplied to food services} = \sum_{1}^{n} \text{RICMs} \times \text{CCVMs} \tag{9}$$

(g) Estimating total annual waste

The total annual waste (TAW) is the sum of waste generated throughout the LVSC (Equation (10)).

$$\text{TAW} = \text{AWP} + \text{AWM} + \text{AWPro} + \text{AWC} \tag{10}$$

Unit: kg/Year

After drawing the model, the parameters were estimated using the Vensim PLE 9.0.0 X64 software.

3.4. Simulate the Model to Test the Scenarios

The simulation period in this model spanned 50 years, from 2022 to 2072, with the year serving as the unit of simulation. At this point, research hypotheses were tested by making necessary modifications to controllable variables in the real world (called scenarios). The purpose of this research was to explore the potential of WRIs within the LVSC. Intervention in this study is defined as actions and modifications that improve waste causes within LVSC. After considering the various causes of waste at each stage, the Pareto principle was initially employed to identify the most significant waste causes. Subsequently, eight interventions were selected from expert opinions to address these waste factors within the LVSC (Table 5). Finally, the potential impact of implementing these interventions to reduce waste in leafy vegetables was assessed by altering specific parameters (e.g., Inadequate weed management) in the model.

Table 5. Individual interventions.

Interventions	Parameter (Waste Causes)	% Variation Applied
Implementing abiotic stress control protocols in farms	Abiotic stresses include water, temperature, and nutritional stress	In these scenarios, it is assumed that in a long-term policy, the current condition of the waste causes will improve by 10% compared to the previous year.
Improving access to educational extension services	Inadequate access to educational and extension services	
Implementing biotic stress control protocols in farms	Pests and diseases Inadequate weed management	
Improving access to quality inputs	Inadequate access to high-quality inputs	
Improving packaging facilities and cold supply chain infrastructure	Lack of proper packaging facilities Short shelf life of the product	
Improving coordination and information sharing among stakeholders	Inadequate coordination and information sharing among stakeholders Poor demand forecasting	
Improving food shopping planning	Inadequate pre-purchase planning Over-purchasing	
Food preparation based on household needs	Excessive food preparation	

Moreover, the quantity of waste generated across the SC phases is impacted by the preceding stages, particularly in the case of perishable items such as leafy vegetables. Implementing measures to reduce waste in the earlier phases will result in decreased spoilage and degradation, ultimately enhancing the product's quality in the later stages and reducing waste during these stages. Since one of the primary factors contributing to waste in this study was the inadequate quality of the leafy vegetables delivered to each stage of the SC, the study also examined the effects of implementing WRIs at each stage on waste reduction in subsequent stages of the LVSC.

4. Results

Before presenting the findings and modeling results, it is essential to confirm the designed model's accuracy. As a result, the findings that confirm the model's validity and accuracy are provided first in this section.

4.1. Model Validity Evaluation

After it has been developed, the model needs to be validated. Expert judgments and specific tests like sensitivity analysis were utilized for this goal. To verify and validate the model in SDM, two categories of behavioral and structural tests are used [72]. The model was structurally and behaviorally tested using a sensitivity analysis test. The behavior of other model variables is examined concerning changes in variables and which values can be changed under real-world circumstances. To do this, during the sensitivity analysis phase, the values of model constants were modified between +10 and −10, and the system output values were assessed. Figure 6 displays the results of the sensitivity analysis for the four key research variables at four different modification levels (50%, 75%, 95%, and 100%). These variables were chosen based on the advice of experts and how sensitive the model was to changes in them. According to these results, the model is reliable because its outcomes are sensitive to changes in the inputs.

The model results must be compared to real-world data after confirming the validity of the simulated model. However, due to the lack of historical data in the current study, the output of the simulation model was evaluated by three subject matter experts to confirm or reject it. Finally, the model was improved based on their feedback.

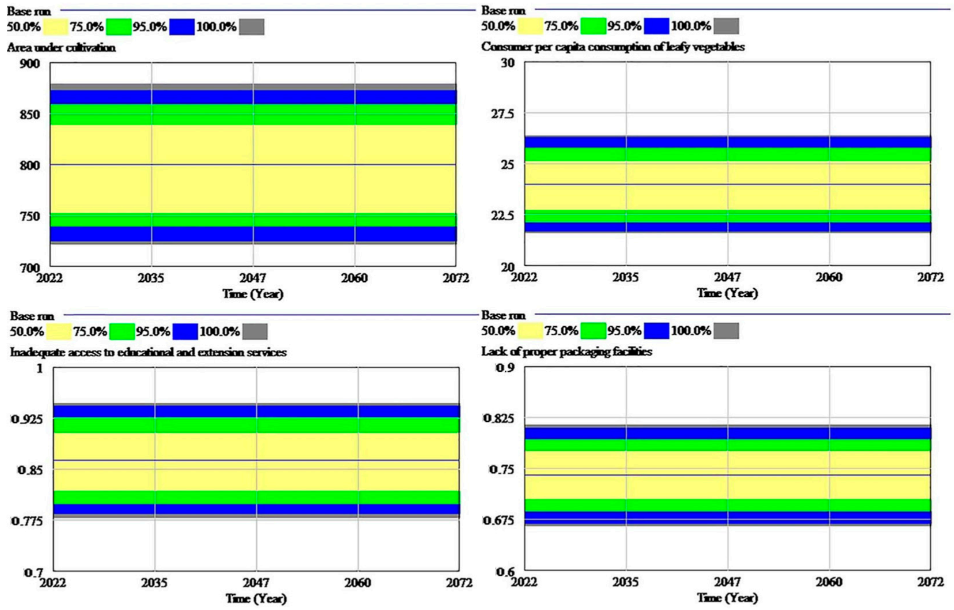

Figure 6. Confidence limits for four of the most important model variables.

4.2. Model Simulation Under Various Scenarios

After formulating the model and confirming its validity, it can be put into practice. The simulation was carried out in two steps. Initially, a baseline simulation was performed to calculate the current volume of waste and its trend during the simulation period. Then, the impact of interventions on waste reduction was evaluated.

4.2.1. Simulation of the Model Under the Baseline

This run simulates the waste generation at various points along the LVSC during the simulation period. According to the findings, an estimated 31,000 tonnes of leafy vegetables are discarded annually across the SC. The three stages of production (12,500 tonnes), consumption (12,300 tonnes), and marketing (5700 tonnes) contribute the highest amount of wasted mass (Figure 7).

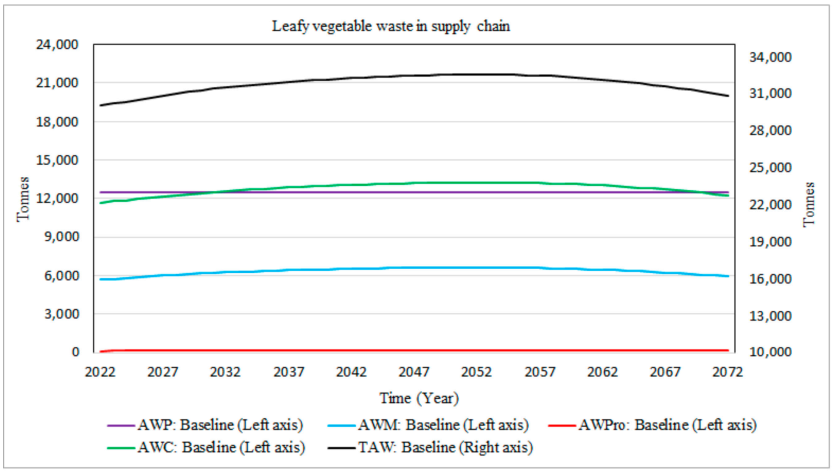

Figure 7. The amount of waste in LVSC.

4.2.2. Potential Effect of Waste Reduction Interventions

Figure 8 demonstrates the effects of the Waste Reduction Intervention scenarios developed in Section 3.4 at each stage of the LVSC. The findings indicate that four interventions significantly contribute to reducing production waste (Figure 8a). These interventions include implementing biotic stress control protocols in farms, improving access to educational-extension services, improving access to quality inputs, and implementing abiotic stress control protocols in farms. Implementing these interventions reduces production waste, improves product quality, and reduces waste in subsequent stages of the LVSC. In the market, improving packaging facilities and cold SC infrastructure, along with enhanced coordination and information sharing among stakeholders, are crucial in minimizing market waste (Figure 8b). Furthermore, the simulation results of combined interventions in other stages of LVSC show that any waste reduction in the production and consumption stages will also reduce market-stage waste. For instance, implementing measures to improve production quality can minimize waste in the market stage. Similarly, interventions to reduce waste in the consumption stage can decrease consumer demand for leafy vegetables, resulting in a reduced flow of such vegetables in the market and ultimately reducing waste in this stage. Most leafy vegetables are consumed in households. At this stage, two interventions that have been recognized as crucial for minimizing waste are improving food shopping planning and preparing food based on household needs (Figure 8c). Moreover, market and production interventions have the potential to play a role in minimizing waste generated during the consumption phase. This decrease in waste can be attributed to higher-quality products being provided to consumers.

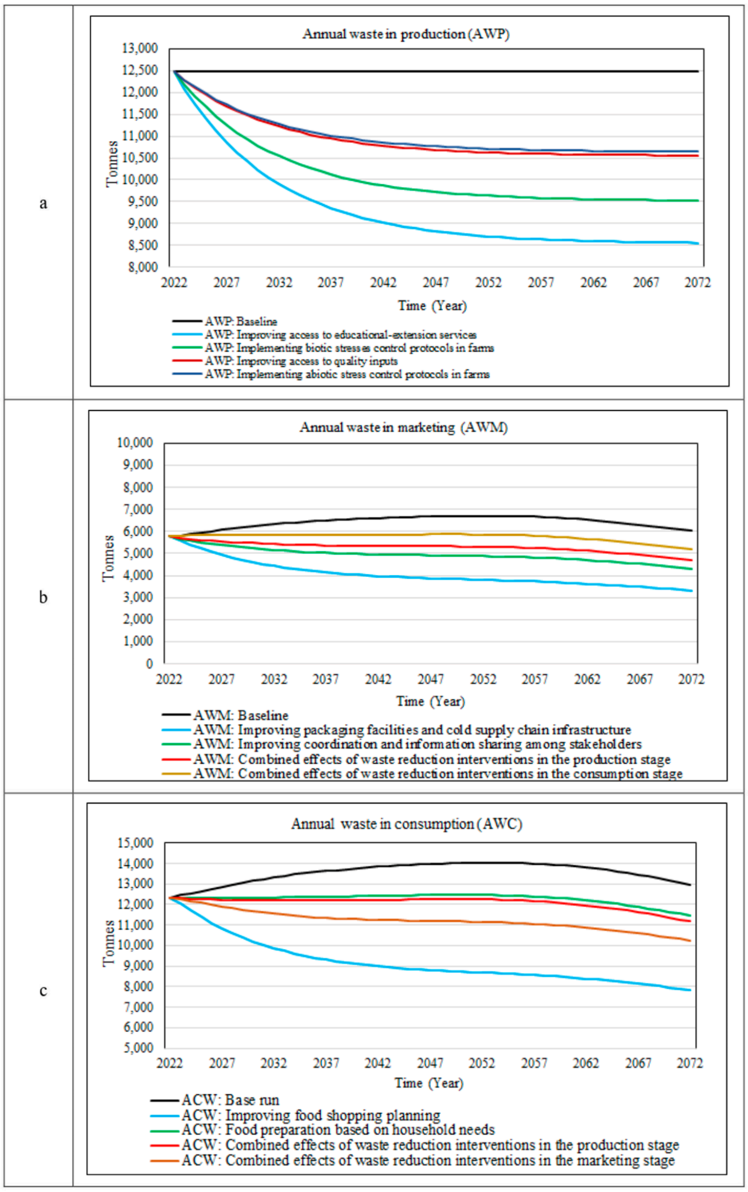

Figure 8. The effects of individual interventions on waste reduction at various stages of the LVSC.

Investigating the effects of WRIs on the total waste in the LVSC showed that improving food shopping planning (by 5800 tonnes/year), implementing biotic stress control protocols in farms (by 5100 tonnes/year), improving packaging facilities and cold SC infrastructure (by 4400 tonnes/year), improving access to educational-extension services (by 3900 tonnes/year), improving coordination and information sharing among stakeholders (by 2800 tonnes/year), improving access to quality inputs (by 2500 tonnes/year), implementing abiotic stress control protocols in farms (by 2400 tonnes/year), and preparing based on household needs (by 1700 tonnes/year), respectively, had the greatest impact on reducing total annual waste (Figure 9).

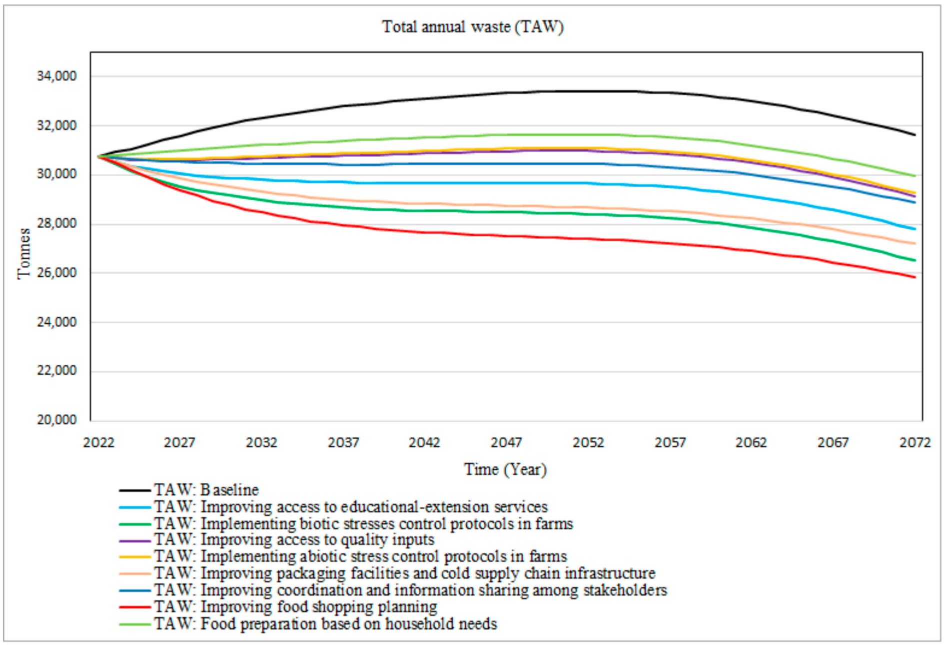

Figure 9. The effects of interventions on total annual waste reduction at various stages of the LVSC.

5. Discussion

Although many researchers have proposed solutions for waste reduction in the FSC, the impact of these interventions has not been documented. This present study introduces an innovative approach that enables the evaluation of the potential impact of Waste Reduction Initiatives (WRIs) within the LVSC.

The results include the following findings:

- Four key interventions significantly reduce production waste: biotic and abiotic stress control protocols, improved access to educational services, and quality inputs.
- Enhanced packaging facilities, cold SC infrastructure, and better coordination in the market reduce market waste.
- In households, effective food shopping planning and preparing food based on needs are crucial to minimizing waste.
- Combined interventions across LVSC stages show that reducing waste in production and consumption also lowers waste in the market stage.
- Higher-quality products from market and production interventions contribute to reduced waste during the consumption phase.
- Below, we discuss these findings in relation to findings from scientific literature.

5.1. Interventions to Reduce Production Waste

The findings identified the production stage, household consumption, and market as key points for waste reduction. Implementing biotic stress control in farms emerged as the most crucial intervention, as pests and diseases pose major challenges by causing physical damage to crops, rendering them unfit for sale, and facilitating disease transmission, which can lead to complete crop failure [32]. These issues underscore the need for effective pest and disease management to maintain the quality of leafy vegetables. Farmers who focus on biotic stress control can ensure a more consistent supply of high-quality produce. Research shows that weeds significantly contribute to agricultural waste by competing with crops for nutrients, water, and sunlight, acting as reservoirs for pests and diseases, and obstructing the harvesting process, leading to increased product losses [73]. Therefore, implementing weed control is crucial in reducing waste from weed-related damage. Enhancing access to education and extension services is also vital, as a significant amount of agricultural waste results from outdated technologies, inadequate farmer training, and lack of knowledge of new production techniques [74]. The issue is exacerbated by the lack of educational and extension services, which limits farmers' knowledge and amplifies other factors that contribute to waste [32,75]. Thus, in line with the Bajželj, et al. [24] proposition, which emphasizes the necessity of imparting relevant training to small-scale farmers, this study proposes that improving access to extension services can serve as a foundation for tackling other waste-related challenges at this stage. Enhancing access to quality inputs like seeds and fertilizer is also crucial for reducing LVW, as farmers often face obstacles such as limited distribution centers and rising input prices [50]. Consequently, enhancing farmers' access to high-quality inputs is crucial for reducing waste. Implementing abiotic stress control in farms is another key intervention, as abiotic stresses during plant growth can severely affect post-harvest quality and lead to food loss [42]. Water stress affects product quality by causing physiological changes in plants by reducing turgor pressure and compromising cell integrity. Research indicates that moisture loss—both pre-harvest and post-harvest—can severely reduce the marketability of leafy vegetables; even a 3–5% reduction in moisture content can make them less appealing to consumers, leading to increased spoilage and waste [76]. Nutritional factors significantly impact post-harvest quality; for example, vegetables from calcium- and potassium-deficient soil have a shorter shelf life [77]. Unfavorable climatic conditions can also affect the appearance of the product, making it unsellable [32]. To reduce these abiotic stresses, it is critical to develop integrated farm management practices that combine agronomic and technological advancements.

5.2. Interventions to Reduce Market-Stage Waste

In the market, the development of packaging facilities and cold SC infrastructure is crucial for reducing waste, as they extend product shelf life by minimizing spoilage [34]. Enhanced packaging not only safeguards products from physical damage during transportation and storage but also significantly extends their shelf life by minimizing spoilage [78]. Moreover, effective cold chain management is essential for preserving the integrity of perishable goods [28]. This strategy is crucial, especially for Leafy vegetables, which are particularly susceptible to quality degradation due to temperature fluctuations.

Improving coordination and information sharing among stakeholders is the second most effective waste reduction strategy, supported by research on fruit and vegetable SCs in Portugal [18]. Effective communication across the SC reduces uncertainty and helps stakeholders quickly respond to demand changes or supply shortages [79]. A major contributor to food waste is the supply—-demand gap, which can be mitigated through better coordination and information sharing. When stakeholders lack access to timely market information, they may make poor decisions regarding pricing and inventory management, leading to unsold perishables and financial losses [33,43]. The cyclical or seasonal nature of agricultural production can further complicate this issue. Long-term demand fluctuations can create boom-and-bust cycles where high prices in one season lead to overproduction in the next, resulting in market surpluses and subsequent price drops [24]. To address these issues, collaborative platforms that facilitate real-time communication among producers, distributors, and retailers can help synchronize supply with consumer demand more effectively. Furthermore, policies that promote cooperative models among producers can enhance information sharing and resource allocation, ultimately leading to a more resilient supply chain.

5.3. Interventions in Consumption Stage

In the consumption stage, food waste often results from quality issues stemming from earlier stages in SC. Addressing these issues early in the SC improves product quality and reduces waste. Enhancing food purchasing planning at the household level is a key measure to mitigate waste. Aschemann-Witzel, et al. [80] found that precise food purchase planning correlates with lower FLW. While not all studies show a direct link, better planning is associated with fewer unplanned purchases [81]. Over-purchasing is a major factor in household food waste. Studies show people often buy excess food for precautionary reasons [39,46]. Additionally, retailer promotions can shift surplus fruits and vegetables to consumers' homes, increasing the risk of quality compromise [2]. Another important intervention to reduce LVW in the household stage was food preparation based on household needs. Numerous studies show that cooking too much food often leads to excess portions being discarded [46].

5.4. Combined Interventions Along LVSC to Reduce LVW

Findings highlight that early-stage factors in the LVSC crucially impact later waste accumulation. Liu (2014) found these factors significantly affect the quality of perishables, while Siddiqui [82] noted that over 70% of product quality in later stages depends on harvesting and pre-harvesting conditions. Therefore, waste reduction strategies should target early stages to prevent later waste. Stakeholder decisions also greatly affect product quality [83]. Since product quality affects waste in later stages, targeted interventions and waste reduction initiatives should be applied at each stage of the LVSC. The findings indicate that using interventions in both production and consumption stages can effectively reduce market waste. Lower waste in production results in fewer low-quality products entering the market, while reducing waste in consumption decreases demand, leading to less market waste. A comprehensive approach addressing both stages can significantly reduce overall SC waste.

Implementing WRIs across the LVSC can lead to excess products at various stages due to shifting waste earlier in the chain. While this imbalance may cause short-term losses, the market will eventually stabilize with reduced cultivation. Developing processing industries could help absorb the excess supply and address short-term LVW.

6. Conclusions

In this study, a framework for evaluating the possible impact of WRIs along the LVSC was developed using the SDM. The novelty of this study lies in its development of a pioneering framework using SDM to evaluate the impact of WRIs across LVSC. This approach not only tracks product flow and identifies critical waste generation points but also assesses cause-and-effect relationships in waste generation. Additionally, this research contributes to existing theories in FLW management by offering a new methodological approach that emphasizes the interconnectedness of early-stage interventions and their impacts on later stages. Conventional paradigms have often segregated FLW management from initial operational decisions; however, the findings of this study indicate how proactive strategies implemented at the early stages of the LVSC can significantly influence LVW reduction across subsequent phases. Therefore, this research not only advances theoretical understanding in the fields of waste management and SC dynamics but also provides a flexible analytical tool for waste assessment and intervention selection that can be applied across various SCs.

Furthermore, the implications of this research extend beyond theoretical contributions. The study implies eight interventions, based on an assessment of the potential impact of WRIs, that have the greatest impact on reducing overall LVW:

(1) Improving food shopping planning,
(2) Implementing biotic stress control protocols in farms,
(3) Improving packaging facilities and cold SC infrastructure,
(4) Improving access to educational extension services,

(5) Improving coordination and information sharing among stakeholders,
(6) Improving access to quality inputs,
(7) Implementing abiotic stress control protocols in farms,
(8) Food preparation based on household needs.

The identified interventions provide practical insights for policymakers and practitioners. Additionally, product quality was a major waste source in various LVSC stages. The most significant waste in later stages stems from earlier-stage practices. Thus, early intervention is crucial for reducing waste in subsequent stages. LVW is widespread in Iran; thus, the Kermanshah province was chosen for the study to offer insights into other regions. The developed framework is broadly applicable and can be adapted to different regions and/or SCs. Key principles and interventions, such as stress control protocols, better educational services, and improved quality inputs, are relevant across the country. Adapting these strategies to local conditions can help reduce FLW in other regions' LVSC.

Despite the contributions mentioned above, it is crucial to comprehend the limitations of this study to guide future research endeavors. Based on the most significant causes connected to these initiatives, this study, which takes a holistic approach, examines the efficient waste reduction practices in various LVSC parts. To further advance the field, future studies could employ agent-based modeling techniques and SDM to analyze various WRIs, model the waste system characteristics, explore the mechanisms of waste generation in different LVSC parts, and investigate stakeholder interactions. Moreover, future research endeavors should address the limitation of this study, which solely assessed the potential impact of actions on waste reduction concerning the identification of primary causes without taking into account the social, economic, and environmental consequences.

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Institutional Review Board Statement: The study was conducted with full consideration of ethical standards. The respondents were informed about the purpose of the research and participated voluntarily, with the freedom to decline to answer specific questions or withdraw from the interview at any point. Since the respondents were only interviewed to provide information during the data-gathering process and no interventions or treatments were performed on them, ethical approval from an institutional review board or ethics committee was not required. This requirement typically applies to psychological or medical research involving interventions or treatments. Additionally, it is worth noting that this study did not involve any animals.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

LVSC, Leafy Vegetable Supply Chain; FLW, Food Loss and Waste; FSC, Food Supply Chain; SC, Supply Chain; WRIs, Waste reduction interventions; SDM, System Dynamic Modeling; LVW, Leafy Vegetable Waste; FGD, Focus Group Discussion; ANP, Analytical network process; RICs, Relative importance coefficients; CCVs, Current condition values; AWP, Annual Waste in Production; DPM, Delivery from Production to Market; DPH, Delivery from production to household; DPPro, Delivery from Production to Processing; AWM, Annual Waste in Marketing; DMH, Delivery from Market to Household; DMPro, Delivery from Market to Processing; DMFS, Delivery from Market to Food Services; AWPro, Annual Waste in Processing; SProC, Delivery from Processing to Consumption; AWH, Annual Waste in Household; TAW, Total Annual Waste; PLVC, Per Capita Consumption of Leafy Vegetables; RICPs, Relative Importance Coefficients of waste causes in the Production stage; CCVPs, Current Condition Values of waste causes in the Production stage; CR, Consistency Ratio; RICMs, Relative Importance Coefficients of waste causes in the Marketing stage; CCVMs, Current Condition Values of waste causes in the Marketing stage; RICPros, Relative Importance Coefficients of waste causes in the Processing stage; CCVPros, Current Condition Values of waste causes in the Processing stage; ACW, Annual Consumption Waste; AC, Annual Consumption; RICHs, Relative Importance Coefficients of waste causes in the Household stage; CCVHs, Current Condition Values of waste causes in the Household stage; RICFSs, Relative Importance Coefficients of waste causes in the Food Services stage; CCVFSs, Current Condition Values of waste causes in the Food Services stage.

Appendix A Development of the Questionnaire

The questionnaire used in this study was developed specifically to address the objectives of our research on the leafy vegetable supply chain. The research process involved two key steps:

1—Initially, we modeled the leafy vegetable supply chain by focus group discussion, which allowed us to identify critical research variables relevant to each stage of the supply chain.

2—Following the identification of these variables, we created a total of 10 questionnaires:

Five questionnaires for actors: These were designed for various stakeholders within the supply chain (Production, Market, Processing, Food services and Household). For example, we asked the following questions to farmers in the production sector:

1—Questions related to the supply chain model for leafy vegetables

1. Area under cultivation of leafy vegetables: .... hectare/m^2
2. Yield of leafy vegetables farms in the last year: .... Tonnes
3. What marketing channels do you use to sell your leafy vegetable products? (a) Direct sales to consumers: .... % (b) Sales to wholesalers: .... % (c) Sales to retail stores: .... % (d) Sales to processing units for leafy vegetables: .... % (e) Exports outside the province: .... % (f) Other (please specify): .... %
4. On average, how many kilograms of leafy vegetables from your farm are lost or wasted out of every 10 kg produced? Amount: .... kg

2—Questions related to identifying the causes of waste in the production sector: Please respond to the following questions about your leafy vegetable cultivation practices on your farm:

	Items	Very Little	Little	Moderate	Much	Very Much
5.1	How often do you irrigate your leafy vegetables farm during hot weather?					
5.2	How frequently do you irrigate your leafy vegetables immediately before harvesting?					
5.3	To what extent do you practice crop rotation in your leafy vegetable cultivation?					

	Items	Very Little	Little	Moderate	Much	Very Much
5.4	To what extent do you apply the appropriate amounts of nitrogen, potash, and phosphate fertilizers on your farm?					
5.5	How suitable are the climatic conditions in your region for growing leafy vegetables?					
5.6	To what extent do plant pests damage your leafy vegetable farm?					
5.7	How much damage do plant diseases cause to your leafy vegetable farm?					
5.8	To what extent do you purchase seeds, fertilizers, pesticides, and other inputs from reputable sources?					
5.9	To what extent do you resort to cheaper inputs when production costs (seeds, fertilizers, etc.) increase?					
5.10	To what extent do you have access to educational and extension courses on leafy vegetable cultivation?					
5.11	To what extent do you have access to educational and extension publications on leafy vegetable cultivation?					
5.12	To what extent does your harvested leafy vegetables face a lack of demand from buyers despite its good quality?					
5.13	How knowledgeable are you about the market demand for leafy vegetable products?					
5.14	To what extent do you employ skilled and trained workers during leafy vegetable harvesting?					
5.15	How often do you harvest leafy vegetables during the hottest times of the day?					
5.16	To what extent is your harvested leafy vegetables exposed to sunlight during harvesting?					
5.17	To what extent do you use appropriate transportation methods to move harvested leafy vegetables on your farm?					
5.18	To what extent have you experienced price fluctuations in the leafy vegetable market?					
5.19	How much damage do weeds cause to your leafy vegetable farm?					
5.20	To what extent do you have access to proper storage facilities for leafy vegetables?					

We also developed five questionnaires for experts (Production, Market, Processing, Food services and Household). These questionnaires focused on gathering insights about the relative importance of different causes of waste at each stage of the supply chain. For further clarification, we have provided the ANP questionnaire for production sector experts below:

ANP questionnaire on the weight of causes of waste in the production sector:

1. Please indicate your opinion on the priority of each cause (i) compared to (j) their impact on waste in the production sector.

j	Priority of j Compared to i (2–9)	Equal Priority	Priority of i Compared to j (2–9)	i
Pests and diseases		1		Abiotic stresses include water, temperature, and nutritional stress
Inadequate access to high-quality inputs		1		Abiotic stresses include water, temperature, and nutritional stress
Inadequate access to educational and extension services		1		Abiotic stresses include water, temperature, and nutritional stress
Production exceeds the market demand		1		Abiotic stresses include water, temperature, and nutritional stress
Improper farm harvesting and handling techniques		1		Abiotic stresses include water, temperature, and nutritional stress
Severe fluctuations in product prices		1		Abiotic stresses include water, temperature, and nutritional stress
Inadequate weed management		1		Abiotic stresses include water, temperature, and nutritional stress
Lack of proper storage facilities		1		Abiotic stresses include water, temperature, and nutritional stress
Inadequate access to high-quality inputs		1		Pests and diseases
Inadequate access to educational and extension services		1		Pests and diseases
Production exceeds the market demand		1		Pests and diseases
Improper farm harvesting and handling techniques		1		Pests and diseases
Severe fluctuations in product prices		1		Pests and diseases
Inadequate weed management		1		Pests and diseases
Lack of proper storage facilities		1		Pests and diseases
Inadequate access to educational and extension services		1		Inadequate access to high-quality inputs
Production exceeds the market demand		1		Inadequate access to high-quality inputs
Improper farm harvesting and handling techniques		1		Inadequate access to high-quality inputs
Severe fluctuations in product prices		1		Inadequate access to high-quality inputs

j	Priority of j Compared to i (2–9)	Equal Priority	Priority of i Compared to j (2–9)	i
Inadequate weed management		1		Inadequate access to high-quality inputs
Lack of proper storage facilities		1		Inadequate access to high-quality inputs
Production exceeds the market demand		1		Inadequate access to educational and extension services
Improper farm harvesting and handling techniques		1		Inadequate access to educational and extension services
Severe fluctuations in product prices		1		Inadequate access to educational and extension services
Inadequate weed management		1		Inadequate access to educational and extension services
Lack of proper storage facilities		1		Inadequate access to educational and extension services
Improper farm harvesting and handling techniques		1		Production exceeds the market demand
Severe fluctuations in product prices		1		Production exceeds the market demand
Inadequate weed management		1		Production exceeds the market demand
Lack of proper storage facilities		1		Production exceeds the market demand
Severe fluctuations in product prices		1		Improper farm harvesting and handling techniques
Inadequate weed management		1		Improper farm harvesting and handling techniques
Lack of proper storage facilities		1		Improper farm harvesting and handling techniques
Inadequate weed management		1		Severe fluctuations in product prices
Lack of proper storage facilities		1		Severe fluctuations in product prices
Lack of proper storage facilities		1		Inadequate weed management

2. Evaluating the impact of some causes on inadequate weed management

j	Priority of j Compared to i (2–9)	Equal Priority	Priority of i Compared to j (2–9)	i
Inadequate access to high-quality inputs		1		Inadequate access to educational and extension services

3. Evaluating the impact of some causes on pests and diseases

j	Priority of j Compared to i (2–9)	Equal Priority	Priority of i Compared to j (2–9)	i
Inadequate access to high-quality inputs		1		Inadequate access to educational and extension services
Abiotic stresses include water, temperature, and nutritional stress		1		Inadequate access to educational and extension services
Abiotic stresses include water, temperature, and nutritional stress		1		Inadequate access to high-quality inputs

For the other stages of the supply chain, we have also developed tailored questionnaires for both actors and experts.

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