

Economic assessment of Chilean agricultural land use, labor demand and input requirements using the Delphi method. Part B: Vegetables for fresh consumption

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ABSTRACT

Among the main food items purchased by households, the market for fresh vegetables plays a strategic role in food security in Chile by ensuring access to healthy and affordable diets. This study aimed to analyze the dynamics of fresh vegetable markets and prices in Chile between 2017 and 2021, with a focus on productivity, farm structure, agrochemical use, and the implications for food system resilience. Using a modified Delphi method, we generated technical-economic estimates that characterize production variability, labor requirements, and agrochemical input intensity. The results reveal high year-to-year volatility in cultivated area, especially in crops with a large number of smallholder farms. Between 2017 and 2021, domestic fresh vegetable production increased from 892 482 to 1 073 472 t, while exports represented only 4.9% and 4.3% of total traded vegetables in those years, underscoring the sector's primary orientation toward domestic consumption. In 2021, the average cultivated area per farm was 0.95 ha for vegetables, compared to 6.39 ha for fruit orchards. Swiss chard, for example, was reported on 983 ha across 3217 farms, chili pepper on 633 ha across 2056 farms, and beetroot on 1321 ha across 2266 farms. Estimated pesticide loads ranged from 10.7 to 15.3 kg active ingredient (ai) per hectare in alliaceous crops and from 2.1 to 9.4 kg ai ha⁻¹ in solanaceous crops such as potato and tomato, with a weighted average of 3.16 to 5.01 kg ai ha⁻¹, aligning with international benchmarks. The sector comprises 109 280 fresh vegetable producers, mostly smallholder farmers, but despite population growth and rising retail prices, the total cultivated area has remained relatively unchanged, highlighting structural challenges to sustainable intensification. The findings emphasize the environmental and economic pressures faced by the vegetable sector and its critical function in supplying domestic markets, reinforcing the need for territorial and policy strategies to strengthen food security.

Key words: Agrochemicals, Delphi method, fresh vegetables, smallholder farmers, vegetable market.

INTRODUCTION

The lack of access to a healthy diet is a major global challenge, affecting over 3.1 billion people in 2022, largely driven by income inequality and resulting in varying degrees of food insecurity worldwide (FAO, IFAD, UNICEF, WFP and WHO, 2024). Food security depends on a holistic approach that integrates availability, economic access, utilization and stability across the food system (Clapp et al., 2022). Globally, food systems must provide affordable and nutritious foods despite constraints imposed by climate change and economic fluctuations (Hailu, 2023).

In Chile, despite a sustained reduction of undernutrition and the implementation of public policies to improve food access in schools and among the elderly, inequalities in access to a healthy diet persist (Margozzini

and Passi, 2017). Fresh vegetables have a crucial role in the food security of Chilean households, contributing to healthy and affordable food (Donoso et al., 2025). Over the past 50 yr, Chilean agricultural land has undergone significant reconversion, with more than 40% of traditional crops such as cereals and legumes being replaced by nuts and fresh fruits for export, while fresh vegetables occupy 79 000 ha as of 2020 (del Pozo et al., 2024), forming the main annual irrigated crops north of the Biobío River across central-north, central and central-south territories (INE, 2022). However, fresh vegetable markets remain highly exposed to seasonality, both prices and labor availability, creating pressures on growers who must decide what vegetables to establish amid rising costs. Projections of the domestic fresh vegetables markets are therefore critical for informed decision-making.

Given the broad diversity of species, productive scales, and territorial heterogeneity, vegetable production presents challenges for comparable assessment of productivity and resource requirements. In this study, a modified Delphi method (Rittirong et al., 2024) was applied to integrate technical-economic indicators and build consensus on yield ranges, labor needs, and input use. The present study aims to examine the productive and market dynamics of fresh vegetables in Chile, projecting the productivity of irrigated land, labor requirements, and the intensity of use of pesticide and fertilizer use. This analysis seeks to contribute to understanding the resilience of the fresh vegetable sector in Chile and its strategic role in national food security.

MATERIALS AND METHODS

International trade assessment

To characterize the international trade of Chile in fresh vegetables, publicly available export and import databases for 2017 and 2021 were analyzed, including nominal USD prices and traded quantities. Each harmonized code associated with these products was classified at the species level and according to the quality of the product as fresh and unprocessed.

For comparability, nominal prices were converted into real prices with December 2024 as the base, incorporating the annual inflation reported by the Central Bank of Chile (2025) using the linked Consumer Price Index (CPI) series and an inflation deflator or correction factor (F_c) (González et al., 2013). The F_c was obtained through the mathematical expression [$F_c = I_{2024}/I_{(i)}$], where: I_{2024} corresponds to accumulated value of the CPI as of December 2024 and $I_{(i)}$ is the accumulated value of the CPI for year I , with $i = 2017$ and 2021 , respectively. The corrected prices in 2024 constant currency were then expressed in USD at the exchange rate in effect in December 2024, equivalent to 992.12 Chilean pesos (CLP) per USD. Interquartile ranges and median values of nominal and real prices per metric tons (t) were estimated for each combination of transaction type, product category, and year.

Assessment of the domestic market for fresh vegetables

To complement the information on international trade, an assessment of the domestic market for fresh vegetables was conducted using data from the Household Budget Survey (HBS) from 2017 and 2021 (INE, 2023), considering only the regional capital cities, which represent over 80% of the formal market and population. The average nominal price paid per kilogram per capita consumption and per capita expenditure were estimated for each category and year. Subsequently, as with international trade prices, nominal values were adjusted for inflation using the Central Bank of Chile (2025) through a F_c as of 31 December 2024, and then converted to USD at the exchange rate on 31 December 2024 of 992.12 CLP per USD.

Sources of information

The collection of technical-economic information was carried out through successive consultation rounds with growers and experts using a modified Delphi methodology (Gibbon et al., 2007). This approach was selected to integrate empirical production data with expert judgment and to iteratively validate technical-economic parameters across heterogeneous production systems.

Initially, Chilean agricultural land was zoned based on georeferenced data from the Centro de Información de Recursos Naturales (CIREN) of the Ministry of Agriculture, including agroclimatic zoning, agricultural soil maps and the geopolitical organization of the territory. Based on this spatial framework, the main productive

categories of fresh vegetables and associated technological levels were identified within each zone to guide field data collection during 2022 and 2023.

For the purposes of this study, and following the guidelines of the VIII Agricultural Census of Chile 2020-2021 (INE, 2022), an Economic Productive Unit (EPU) was defined as a silvoagropecuarian production unit under unique management by a grower, with a cultivated area equal to or higher than 2 ha and/or registered agricultural sales during the previous year.

Within this framework, the modified Delphi process was implemented through three sequential consultation rounds, following the approach described by González et al. (2013) to construct technical-economic standards for fresh vegetables production systems.

First Delphi consultation round

The first round of structured open-ended questionnaires aimed at identifying the key components required to build technical-economic standards, including crops yields, pesticides and fertilizer use, tillage and cultural operations, labor requirements, and estimated workdays per hectare for both human labor and tractor use.

This questionnaire was applied to 67 Economic Production Units (EPUs) corresponding to fresh vegetables growers affiliated with extension and technology transfer groups from Instituto de Investigaciones Agropecuarias (INIA) (GETs) and private agricultural companies. The EPUs were stratified by productive category and edaphoclimatic zone, ensuring representation of the main vegetable production systems and agroecological conditions.

Responses were systematized and complemented with secondary technical information from the INIA institutional library, including sectorial interviews, technical bulletins, extension manuals, and crop management guidelines. Based on this combined information, reference technical-economic standards were constructed on a per-hectare basis, incorporating crop type and variety, technological level, orchard size, yields, and economical costs associated with labor, tractor use, pesticides and fertilizers.

Second Delphi consultation round

In a second round, the preliminary standards were submitted for evaluation to a panel of 16 consultants and subject matter experts, forming a public-private expert group composed of professionals from Instituto de Desarrollo Agropecuario (INDAP) Technical Assistance Services (SAT), INDAP Local Development Programs (PRODESAL), Regional Ministerial Secretariats (SEREMI) and INIA.

Experts assessed the standards in terms of technical coherence, economic plausibility, and regional representativeness, providing qualitative feedback and quantitative adjustments. Revisions were incorporated iteratively, and convergence among expert opinions was used as a criterion for consensus, consistent with Delphi-based validation procedures.

Geographic coverage review and standards validation

Geographic representativeness of the standards was subsequently reviewed by the National Irrigation Commission (CNR). This review identified gaps in territorial coverage, prompting additional targeted data collection in underrepresented zones. Finally, a third consultation round was conducted with an independent group of vegetable production experts to confirm robustness, internal consistency, and applicability of the finalized technical-economic standards.

Elaboration of technical-economic standards and data analysis

Reference technical-economic standards were developed for each factor combination by means of the software Serie MiniSoft EconoINIA Hortalizas (González and Donoso, 2024). The software was employed to systematize primary and secondary information on labor requirements, tractor cultural operations, and fertilizers and pesticides used, and to standardize technical coefficients in order to compute per-hectare technical indicators across crops, technological levels and agroclimatic zones.

The resulting standards were organized in a structured database, establishing minimum-maximum ranges for yield, man-days per hectare (man-days ha⁻¹), tractor-days per hectare (tractor-days ha⁻¹), tons of fertilizers applied per hectare (t ha⁻¹), and kilograms of active ingredient applied per hectare (kg ai ha⁻¹). For vegetables

with limited cultivated area, where empirical ranges could not be directly obtained through the modified Delphi process, a 5% confidence interval around expert-elicited reference values was applied.

Descriptive statistical analysis was used to summarize central tendencies and variability of the technical coefficients, supporting the construction of representative and internally consistent standards. To contextualize the results, the derived standards were compared and with technical-economic references from major vegetable-producing regions under Mediterranean climates, including studies from the University of California, Davis, California Agricultural & Resource Economics Department (UC Davis, 2025).

Projection of full-yield area

To project the surface under full yield by species of fresh vegetables per year, the projected domestic demand in tons for 2017 and 2021 was considered, together with exported quantities of fresh vegetables for the corresponding year, minus the corresponding imports. Full-yield area was defined as the surface required to produce these quantities, using the yield ranges obtained from the modified Delphi methodology.

The projected full-yield surfaces were contrasted with data from the VIII Agricultural Census of Chile 2020-2021 (INE, 2022), to adjust the projections to a range of the most probable full-yield area for the period 2017-2021. This comparison allowed integration of international trade data with domestic consumption of nuts and fresh vegetables and with census-reported surfaces.

Using the adjusted full-yield surface ranges and the reference technical-economic standards developed, probable annual labor requirements were projected, expressed as 260 work-days of 8 h per job. Similarly, tractor labor requirements were projected, expressed as 260 tractor-days of 8 h per job, based on the conversion of hours of use. Annual use of fertilizers and kilograms of active ingredients per hectare was also estimated according to the technical coefficients per species and area.

Within these ranges, elemental S and horticultural oils were not included, as no maximum residue levels (MRLs) are established for these products, following Annex IV of Regulation (EC) N°396/2005 of the European Union (European Food Safety Authority; EFSA et al., 2023), despite their widespread use in high quantities. The impact of these variables on the resilience of the sector is addressed in the Results and Discussion section.

RESULTS AND DISCUSSION

In 2017, the Household Budget Survey (HBS) from INE registered 121 627 transactions of fresh vegetables, a number that declined to 114 467 in 2021; these transactions along with the international trade were the ones analyzed. Regarding international trade, 348 export transactions of fresh vegetables were reported in 2017 and 165 in 2021, while import transactions increased from 295 in 2017 to 430 in 2021, indicating a rise in imports and a decline in exports.

Between 2017 and 2021, domestic fresh vegetable production showed an upward trend, increasing from a projected 892 482 t in 2017 to 1 073 472 t in 2021 (Figure 1). The growth in production mirrors population expansion, which rose from 18 419 192 people in 2017 to 19 678 363 in 2021 (Central Bank of Chile, 2025), and an increase in per capita consumption of fresh vegetables from 48.45 kg in 2017 to 54.55 kg in 2021 (Table 1). This pattern aligns with global trends, which report a 1.2% growth in fresh vegetable production, despite a 3.6% decrease in the European Union and a 3.3% reduction in USA, attributed to pandemics effects, rising production costs, and logistical challenges (van Rijswick et al., 2024). Consequently, the real value of the domestic Chilean fresh vegetable market reached US\$1269 million by 2021.

Exports of fresh vegetables accounted for 4.9% and 4.3% of total projected fresh vegetables traded in Chile in 2017 and 2021, respectively. Although below the global average of 7% exported vegetables, including both fresh and processed vegetables (van Rijswick et al., 2024), Chilean fresh vegetables exports represented a market value of roughly US\$55 million in 2021.

The ranking of the vegetables most acquired by Chilean household remained stable, led by potatoes, tomato, onions, lettuce and carrots (Figure 1). Potato production for the domestic market is projected at 286 135 t in 2017 and 376 855 t in 2021. Additionally, in 2021, increased consumption of Chilean traditional vegetables, such as choclo corn (44 075 t) and winter squash (39 811 t) was observed.

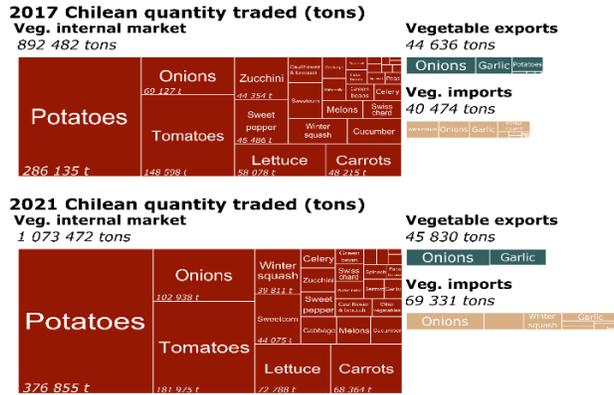


Figure 1. Trade volumes of fresh vegetables traded by market type and year. Details are provided for the main agricultural sector, where 1 mm² equals 500 t.

Table 1. Estimated area in full-yield production by fresh vegetable sector for pre- and post-pandemic scenarios. EPU: Economic productive unit.

Species	Yield	Chile per capita acquisition		Full-yield estimated surface		Surveyed area	
		2017	2021	2017	2021	2021	EPU
	t ha ⁻¹	kg	kg	ha	ha	ha	EPU
Potatoes	10-40	16	19	40 307	47 195	36 206	24 506
Tomatoes	4-30	8.07	9.25	8 191	9 057	5 560	6 848
Onions	15-120	3.75	5.23	5 098	6 283	6 191	3 512
Lettuce	1-50	3.15	3.70	4 383	4 984	4 774	6 045
Winter squash	10-40	1.56	2.02	4 133	4 751	4 986	2 260
Carrots	20-100	2.62	3.47	2 283	2 937	2 710	1 354
Garlic	8-18	0.09	0.35	976	1 886	2 441	2 629
Sweetcorn	10-20	1.30	2.24	3 963	6 639	5 234	3 775
Green bean	5-12	0.49	0.42	2 975	2 509	3 354	4 090
Cabbage	15-60	0.54	0.97	830	1 433	1 527	1 607
Asparagus	5-12	0.08	0.14	430	763	3 861	655
Celery	20-40	0.47	0.65	602	807	919	549
Cauliflower and broccoli	3-7	0.92	0.65	2 823	1 924	3 537	1 730
Sweet pepper	5-40	2.52	0.84	2 572	830	820	1 036
Swiss chard	10-25	0.75	0.48	1 526	950	983	3 217
Zucchini	20-35	2.41	0.81	2 454	797	822	1 296
Faba beans	2-10	0.32	0.22	1 217	817	1 321	2 266
Beetroot	15-25	0.29	0.39	590	778	1 022	1 322
Spinach	10-20	0.21	0.32	431	628	454	808
Melons	10-30	0.78	0.91	1 566	1 714	1 457	890
Artichoke	10-40	0.05	0.20	145	605	953	286
Cucumber	5-40	1.44	0.84	1 078	546	465	1 331
Watermelon	15-40	0.55	0.49	1 265	318	1 776	976
Chili pepper	5-30	0.06	0.07	128	141	633	2 056
Peas	2-10	0.19	0.18	1 152	1 072	1 384	2 372
Veg. garden						1 899	23 665
Other vegetable		0.29	0.54			3 665	8 199

Rising domestic demand corresponded with a 71% increase in fresh vegetables imports from 2017 to 2021, primarily onions and melons. Due to the seasonality of production and limited international transactions, real prices in both domestic and export markets displayed high volatility. As expected, domestic market prices were higher than free on board (FOB) prices, particularly for the other fresh vegetables category (Figures 2 and 3).

Most fresh vegetables fall within the interquartile prices ranges of US\$0-1250 t⁻¹ and US\$1250-2500 t⁻¹. Among exported vegetables, garlic and onion are the only products exported in fresh that hold economic significance, but differ in price levels. Garlic ranks highest (Figure 2), with a median FOB real price US\$2041 t⁻¹ in 2017 and US\$1 878 t⁻¹ in 2021, and high median domestic prices of US\$8161 t⁻¹ in 2017 and US\$3668 t⁻¹ in 2021. In contrast, onions rank among the lowest prices (Figure 2), with median FOB real prices of US\$312 t⁻¹ in 2017 and US\$417 t⁻¹ in 2021, and domestic median real prices of US\$999 t⁻¹ in 2017 and US\$1185 t⁻¹ in 2021. Despite similar agronomic management and higher price incentive for garlic, only onions were exported in large quantities, reaching 34 931 t in 2021, while domestic consumption was 102 938 t (Figure 2). Garlic exports, in comparison, were 23 182 t with a projected domestic volume of 6947 t. This discrepancy is likely linked to the lack of innovation in Chilean garlic (*Allium sativum* L.) production, as no certified varieties or seed production exists, with limited volumes of garlic bulbs used as seed and widespread virosis issues in traditional crops (Madariaga et al., 2023).

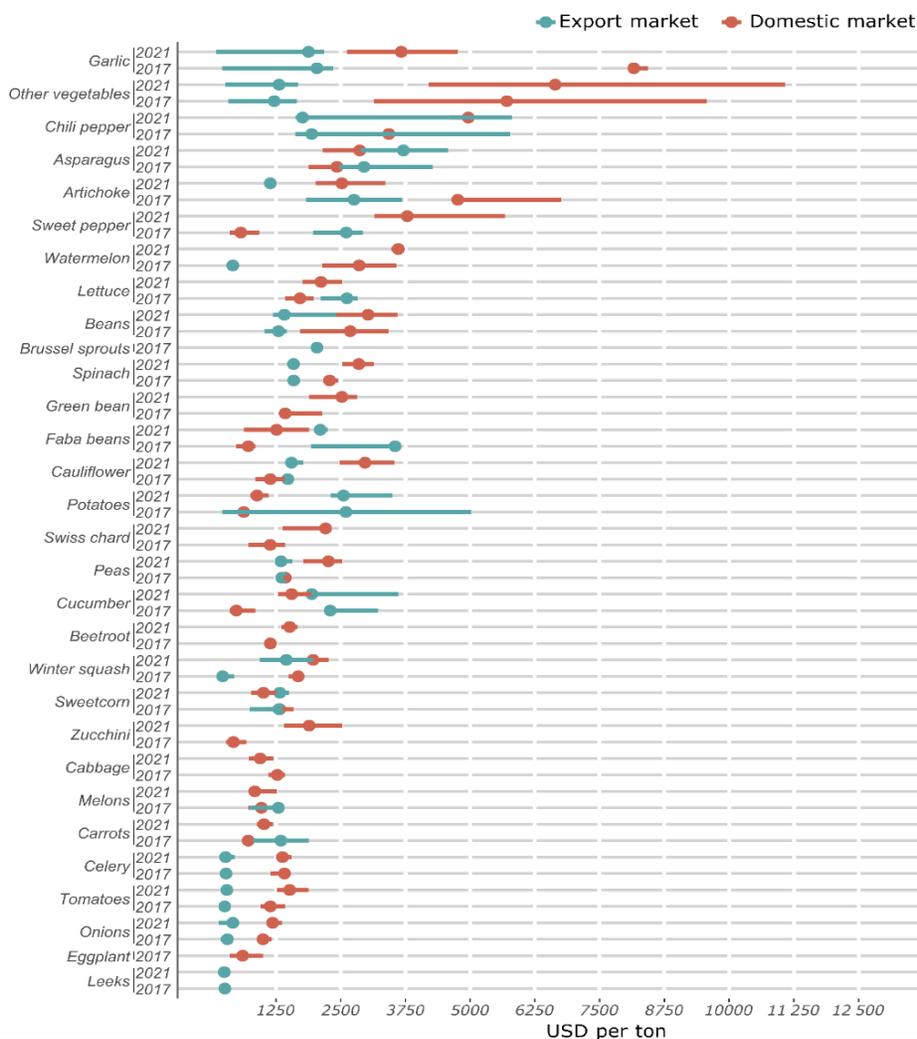


Figure 2. Median real prices comparison between export and domestic markets for Chilean fresh vegetables. Prices are adjusted to December 2024.

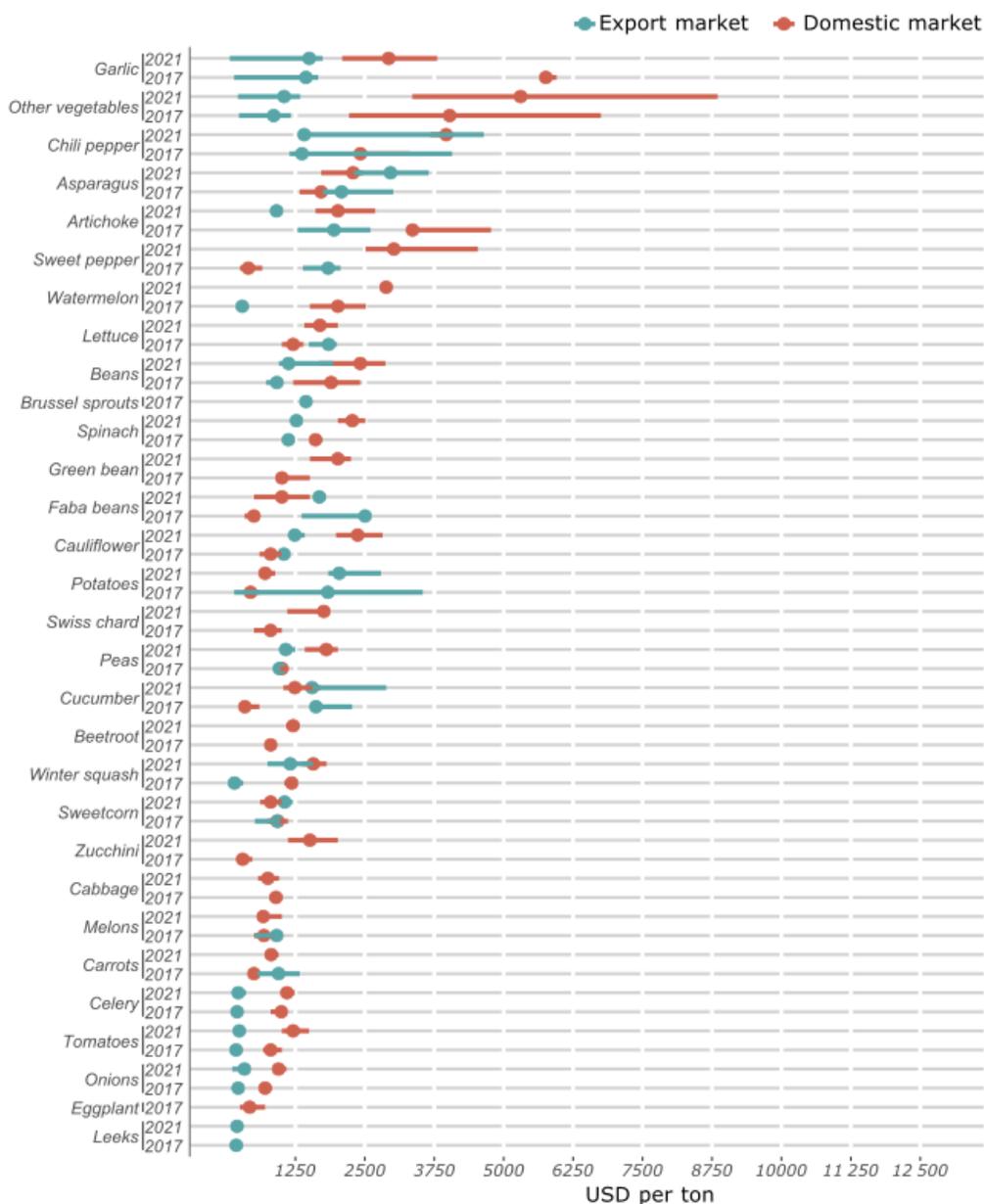


Figure 3. Median nominal price comparison between export and domestic markets for Chilean fresh vegetables.

Projected full-yield surface

In the case of the fresh vegetables sector, the strong seasonality of crops, the rotation of one or more crops cycles per year, growers' decisions, and the high variability in yields associated with outbreaks of pests and diseases, as well as climatic events, make it complex to project the cultivated surface per year for each vegetable crop. Based on the technical-economic yield standards for each vegetable crop, a projected surface at full yield was estimated on the basis of one production cycle per year (Table 1), considering per capita consumption of fresh vegetables extrapolated to the Chilean population, together with quantities traded internationally. The projected full-yield surface for each vegetable crop during the 2017-2021 period was consistent with the surveyed surface in the 2020-2021 census (INE, 2022), especially for the most consumed vegetables, that are potato, tomato, onions, lettuce, winter squash, carrots, garlic and corn. These

vegetables overlap with the most traded fresh vegetables internationally, namely potato, tomato, onions and shallots, cabbage and other brassica vegetables, lettuce and chicory, carrots, and radishes (van Rijswijk et al., 2024).

In contrast, vegetables with lower household consumption exhibited high volatility in per capita demand between 2017 and 2021, even though the 2021 surveyed surface generally fell within the projected full-yield surface. Instability was particularly evident in vegetable crops with a high number of producers, Economic Productive Units (EPUs), especially where the number of EPUs exceeded the number of cultivated hectares (Table 1). Such patterns reflect both the challenge of measuring plots smaller than 1 ha and the structural fragmentation of the fresh vegetables sector. Representative cases include Swiss chard with 983 ha distributed in 3217 EPUs; chili pepper with 633 ha in 2056 EPUs; and beetroot with 1321 ha in 2266 EPUs. On average, fresh vegetables were grown on 0.95 ha per surveyed EPU, compared to fresh fruits, where one EPU managed on average 6.39 (INE, 2022).

This discrepancy between household budget survey projections and surveyed surface may also be influenced by seasons with larger planted areas but lower yields, or by consumer price increases that reduce demand for certain vegetables. To capture this variability, both information sources were integrated into broad ranges of projected full-yield surface for 2017-2021, reflecting the volatility observed over those years. For instance, Swiss chard ranges from 950 to 1500 ha, chili pepper from 50 to 600 ha, and beetroot with 600 to 1000 ha. Assessing land use dynamics is therefore critical, not only to monitor trends in agricultural land use, but also to understand how long-term structural pressures on horticultural land, such as water scarcity and urban sprawl, may compromise the availability, diversity, and affordability of fresh vegetables, with direct implications for national food security and dietary diversity (del Pozo et al., 2024).

Labor requirements associated with fresh vegetables

Labor for fresh vegetables is highly seasonal, driven by the specific agronomic tasks required throughout each crop cycle, which vary in timing and intensity. Consequently, technical-economic ranges of work-days ha⁻¹ and tractor-days ha⁻¹ were determined, accounting for variations in technology levels and production scales (Table 2). Weighted average work-days ha⁻¹ ranged from 39 to 96, depending on crop type, establishment method, continuous sowing or transplanting, and the duration and intensity of the harvest period. Vegetable crops with continuous harvest cycles and transplant-based establishment, such as greenhouse tomatoes or sweet peppers for fresh consumption, required the highest labor input, reaching up to 341 work-days ha⁻¹, due to labor-intensive operations including transplanting, vine guiding, upshoot management, and ongoing harvest. Tractor labor also exhibited considerable variability, with a weighted average between 2.23 and 7.65 tractor-days ha⁻¹. Differences in production scale and technological adoption are illustrated by garlic, where smallholder farmers managing plots under 1000 m², traditionally perform manual sowing and harvest, requiring only 1.56 tractor-days ha⁻¹, whereas larger producers with plots exceeding 1 ha, reported performing mechanized bulb sowing and harvest, totaling 9.25 tractor-days ha⁻¹ (Table 2).

Based on the projected full-yield surfaces for 2017 and 2021, total labor requirements for the sector were projected at 12 308 to 43 657 man-equivalent jobs per year, encompassing all tasks associated with vegetable production. While mechanized operations across the sector were projected between 724 and 3638 equivalent jobs per year, accounting for all tractor-related tasks. These estimates encompass the 85 615 EPUs of fresh vegetable growers surveyed in 2021 across the country, largely smallholder farmers managing their own or rented land, for whom this sector represents both a primary source of income and a means of livelihood.

Table 2. Estimated agricultural labor and tractor use by fresh vegetable sector in full-yield production for pre- and post-pandemic scenarios.

Species	Surface range 2017-2021	Workforce		Machine labor units	
	ha	man-day ha ⁻¹	jobs yr ⁻¹	tractor-day ha ⁻¹	tractor-jobs yr ⁻¹
Fresh vegetables	82 450-120 350	39-94	12 308-43 657	2.28-7.86	724-3 638
Potatoes	36 200-47 200	40-72	5 569-13 071	2.73-10.80	380-1 961
Tomatoes	5 550-9 050	38-341	811-11 869	1.50-8.99	32-313
Sweetcorn	3 950-6 650	35-43	532-1 100	1.83-5.25	28-134
Onions	5 100-6 300	27-92	530-2 229	2.95-9.49	58-230
Winter squash	4 150-5 000	56-77	894-1 481	1.66-2.25	26-43
Lettuce	4 400-5 000	39-64	660-1 231	0.63-2.25	11-43
Asparagus	450-3 850	43-47	74-696	2.62-8.97	5-133
Cauliflower and broccoli	1 900-3 500	41-47	300-633	4.35-13.30	32-179
Green bean	2 500-3 350	43-206	413-2 654	0.96-4.86	9-63
Carrots	2 300-2 950	44-164	389-1 861	3.62-9.25	32-105
Sweet pepper	850-2 550	82-90	268-883	4.04-4.46	13-44
Garlic	1 000-2 450	68-92	262-867	1.56-9.38	6-88
Zucchini	800-2 450	34-38	105-358	3.75-4.75	12-45
Watermelon	300-1 800	79-90	91-623	1.75-3.56	2-25
Cabbage	850-1 550	46-70	150-417	1.31-7.32	4-44
Melons	1 450-1 700	75-90	418-588	2.50-5.50	14-36
Swiss chard	950-1 500	60-66	219-381	2.47-2.73	9-16
Peas	1 100-1 350	27-70	114-363	2.25-4.00	10-21
Faba beans	800-1 300	27-47	83-235	2.37-2.80	7-14
Cucumber	450-1 050	82-90	142-363	4.04-4.46	7-18
Beetroot	600-1 000	5-10	12-38	4.47-4.94	10-19
Artichoke	150-950	82-90	47-329	5.70-6.30	3-23
Celery	600-900	48-54	111-187	3.21-3.55	7-12
Chili pepper	150-650	82-90	47-225	4.04-4.46	2-11
Spinach	450-650	38-42	66-105	2.21-2.45	4-6
Vegetable garden	1 850-1 950	0-40	0-300	0-0.60	0-5
Other vegetables	3 600-3 700	0-40	0-569	0-0.60	0-9

Use of fertilizers and pesticide active ingredients

Following the methodology applied to project labor requirements for the fresh vegetables sector, ranges were also estimated for fertilizers and pesticides active ingredient use per hectare for each vegetable crop (Table 3). These projections aim to capture overall trends in fertilizer and agrochemical load in vegetable production, without replacing specialized methodologies for environmental sustainability assessment.

For fertilizers, fresh vegetables show a projected weighted average use of 0.62 to 2.27 t ha⁻¹ (Table 3). Part of this variability arises from the widespread application of mixed fertilizers with low N content, such as 07-20-20 or 15-20-20, and from the need to apply N in the nitrate form, particularly in ammonia-sensitive species. Fertilizer sources containing only about 15% N t⁻¹, or less, are often blended with other fertilizer that contains no N at all. Among climate change adaptation strategies, fertilizer management, together with irrigation, is one of the most effective agronomic practices, allowing improved nutrient management and yield increases of up to 40%. And

unlike irrigation, fertilizer-based adaption does not require substantial infrastructure investments (Rezaei et al., 2023).

Table 3. Estimated use of fertilizers and pesticide active ingredients by fresh vegetable sector product in full-yield production for pre- and post-pandemic scenarios.

Species	Surface range 2017-2021 ha	Fertilizers		Pesticides	
		t ha ⁻¹	t yr ⁻¹	kg ai ha ⁻¹	t ai yr ⁻¹
Fresh vegetables	82 450-120 350	0.62-2.27	198-1050	3.16-5.01	1 002-3 375
Potatoes	36 200-47 200	0.61-3.40	85-617	2.05-8.67	285-1574
Tomatoes	5 550-9 050	1.15-2.96	25-103	4.91-9.40	105-327
Sweetcorn	3 950-6 650	0.41-1.50	6-38	3.26-4.76	50-122
Onions	5 100-6 300	0.70-1.91	14-46	14.46-15.34	284-372
Winter squash	4 150-5 000	0.95-1.41	15-27	1.17-6.10	19-117
Lettuce	4 400-5 000	0.70-0.95	12-18	2.27-4.66	38-90
Asparagus	450-3 850	1.28-1.42	2-21	6.56-7.26	11-108
Cauliflower and broccoli	1 900-3 500	0.65-1.30	5-18	4.05-6.36	30-86
Green bean	2 500-3 350	0.32-0.72	3-9	1.56-6.61	15-85
Carrots	2 300-2 950	0.20-2.00	2-23	1.12-3.25	10-37
Sweet pepper	850-2 550	1.15-2.96	4-29	4.91-9.40	16-92
Garlic	1 000-2 450	0.61-2.29	2-22	10.66-12.21	41-115
Zucchini	800-2 450	0.67-0.74	2-7	1.10-1.22	3-11
Watermelon	300-1 800	1.86-2.06	2-14	2.66-2.94	3-20
Cabbage	850-1 550	0.65-1.20	2-7	5.01-5.46	16-33
Melons	1 450-1 700	0.45-1.80	3-12	3.14-3.47	18-23
Swiss chard	950-1 500	0.38-0.42	1-2	0.96-1.06	4-6
Peas	1 100-1 350	0.23-0.60	1-3	1.57-4.13	7-21
Faba beans	800-1 300	0.05-0.05	0-0	1.57-4.13	5-21
Cucumber	450-1 050	1.00-1.11	2-4	5.07-5.60	9-23
Beetroot	600-1 000	2.76-3.06	6-12	6.75-8.73	16-34
Artichoke	150-950	0.86-0.95	0-3	2.92-3.22	2-12
Celery	600-900	0.71-0.79	2-3	5.29-5.85	12-20
Chili pepper	150-650	1.15-2.96	1-7	4.91-9.40	3-24
Spinach	450-650	0.71-0.78	1-2	1.14-1.26	2-3
Vegetable garden	1 850-1 950	0-0.05	0-0	0-0.05	0-0
Other vegetables	3 600-3 700	0-0.05	0-1	0-0.05	0-1

Across all vegetable species evaluated, the weighted average pesticide load ranged from 3.16 to 5.01 kg ai ha⁻¹. Among the most widely cultivated vegetable crops, the solanaceous crops of spring-summer potato and tomato, exhibit high pesticides requirements, with 2.1-8.7 and 4.9-9.4 kg ai ha⁻¹, respectively. These figures are comparable to reports from California, where pesticide use in potatoes reaches 9.5 kg ai ha⁻¹ of phytosanitaries during the crop cycle, plus an additional 80 kg ai ha⁻¹ from fumigation prior to planting (UC Davis, 2025). As in fertilizer use, climate change has driven alterations in the usage of pesticides in the past decades, as a response to increased occurrence and severity of the outbreaks of crops pest and diseases, and pesticide use is expected to rise by the end of the century (Wang et al., 2022).

For fresh tomatoes, reported use is 11.7 kg ai ha⁻¹, primarily linked to herbicides applied before crop establishment (UC Davis, 2025). In both cases, soil-active herbicides based on ingredients such as

pendimethalin, metolachlor, or halosulfuron are considered by the Delphi panel as essential in soils with a heavy weed seed bank or under furrow irrigation, where irrigation water often disperses weed seeds. In other situations, part of the herbicide use can be replaced by mulching or weed-suppressing covers.

By contrast, the Delphi panel identified the highest pesticide use in allium crops, particularly onion and garlic, both autumn-winter crops grown for export and domestic markets. For onions, pesticide use ranged from 14.5-15.3 kg ai ha⁻¹, while garlic required 10.7-12.2 kg ai ha⁻¹. The elevated load in both crops is mainly due to preventive and curative applications of fungicides containing mancozeb and metalaxyl. These figures align with California reports of 10.8 kg ai ha⁻¹ for onions, also related with mancozeb-based fungicides (UC Davis, 2025).

Among revisions by the European Union Commission Implementing Regulation by the Regulation 2020/2087 (EU, 2020) decided to withdraw authorization for use of mancozeb as a plant protection in vegetables. An ongoing renewal evaluation for maximum residue levels (MRLs) for most of the fungicides used in vegetables is expected to be sanctioned to 2027, as stated in the Commission Implementing Regulation 2025/787 (EU, 2025).

CONCLUSIONS

Fresh vegetable production in Chile has shown steady growth, driven by population increase, higher per capita consumption within the country, and rising relative prices. This dynamic contrasts with the trend observed in the European Union and USA, where, despite the expansion of the fresh vegetable market, annual production has recorded systematic declines.

According to the latest census, the sector is composed of 109 280 fresh vegetable producers, sustaining a productive area ranging from 82 450 to 120 350 ha. In 2021, this production supplied Chilean households with at least 1 073 472 t of fresh vegetables, valued at US\$1269 billion. To maintain this production level, an estimated 13 032 to 47 295 annual jobs are required, reflecting the high heterogeneity of the sector.

These results confirm the strategic role of horticulture in the food security of Chile while highlighting the main challenges for its sustainability. In contrast to the EU and USA, where declining domestic production has been partially offset by international trade, Chilean fresh vegetable supply remains largely dependent on national production, increasing the relevance of local technical-economic conditions for national food security. This dependence is further threatened by climate change, due to increasing constraints on water availability and production stability, along with an increased occurrence and severity of crops pest and disease outbreaks, reinforcing the need for adaptive technologies aimed at climate change resilience. Key issues include the high degree of production fragmentation, tied to an equally atomized market whose main destination is Chilean households, as well as marked vulnerability to fluctuations in agricultural input costs and market prices. Additionally, the sector requires new technologies, such as improved varieties and agrochemicals with lower active ingredient loads per hectare, which could strengthen its competitiveness.

Author contribution

Conceptualization: A.D., J.G. Methodology: A.D., J.G. Software: A.D. Validation: A.D. Formal analysis: A.D. Investigation: A.D., J.G., J.L. Resources: A.D. Data curation: A.D. Writing-original draft: A.D., J.G. Writing-review & editing: J.G., J.L. Visualization: A.D. Supervision: J.G. Project administration: J.G., A.D. Funding acquisition: J.G. All co-authors reviewed the final version and approved the manuscript before submission.

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