DEPARTMENT OF INTERNATIONAL AND EUROPEAN ECONOMIC STUDIES

ATHENS UNIVERSITY OF ECONOMICS AND BUSINESS

Reducing Post-Harvest Food Losses as a Pathway Towards Net-Zero Agriculture: Socioeconomic and Environmental Insights from FABLE Modeling

Theofanis Zacharatos

Ginevra Coletti

Konstantinos Dellis

Phoebe Koundouri

Working Paper Series

25-47

June 2025

Reducing Post-Harvest Food Losses as a Pathway Towards Net-Zero Agriculture: Socioeconomic and Environmental Insights from FABLE Modeling

Theofanis Zacharatos[1,2,*], Ginevra Coletti [3,4], Konstantinos Dellis[1,2] and Phoebe Koundouri [1,2]

[1] ReSEES Research Laboratory, School of Economics, Athens University of Economics and Business, 10434 Athens, Greece
[2] Sustainable Development Unit, Athena Research Center, 15125 Athens, Greece
[3] Department of Economics and Management, University of Ferrara, Ferrara, Italy
[4] Department of Sciences, Technology and Society, Scuola Universitaria Superiore IUSS Pavia, Pavia, Italy
*Corresponding author

Abstract
The agricultural sector contributes to global greenhouse gas emissions while facing pressures to meet nutritional needs of the growing population. Reducing post-harvest food losses represents an underappreciated path to achieving net-zero emissions without requiring radical changes in production systems. In this study, the Food, Agriculture, Biodiversity, Land-Use, and Energy (FABLE) Calculator simulates post-harvest loss (PHL) reduction scenarios, assessing their socioeconomic and environmental impacts. We model five pathways: a business-as-usual pathway entitled Current Trends, two scenarios with 25% and 50% PHL reductions, and two National Commitments pathways, combining PHL reduction with other policies. Results show that reducing PHL alone lowers production needs and costs by increasing supply chain efficiency. However, only the NC-25% pathway achieves greater cost savings and emission reductions, underscoring the value of combining supply- and demand-side interventions. Ultimately, this study underscores that reducing post-harvest losses is linked to achieving many SDGs and is essential for transitioning to more sustainable agri-food systems.

1. Introduction

According to the Food and Agriculture Organization of the United Nations (FAO), food loss and waste (FLW) is defined as the quantitative or qualitative degradation of food related to decisions made throughout the food supply chain [1]. Post-harvest food losses (henceforth PHL) refer to losses that occur after harvest and before food reaches the final stage of consumption. The causes of PHL and the stages at which they occur are numerous and vary depending on the supply chain, the location and a variety of other contexts. Damage or loss can occur during all post-harvest stages [2]. It is well-documented that PHL stem from multiple, often interrelated causes, including mechanical damage during harvest and transport, improper handling practices, pest and disease infestations, suboptimal environmental conditions (e.g., temperature and humidity), and inadequate storage facilities [1,2]

Available data highlight that the annual PHL ranges from 8% to 23%, depending on the country and geographical area under examination. For instance, in Western Africa, the percentage of PHL amounts to 23.56%, while in Northern America and Europe the percentage is 9.19%. Available data for 2021 (Fig. 1) indicate that globally PHL amount to 13.23% of total food production, while the problem is detected in all regions, highlighting its universality [3,4]. As far as it concerns the food categories, fruits and vegetables are the most susceptible to loss due to their vulnerability [5].

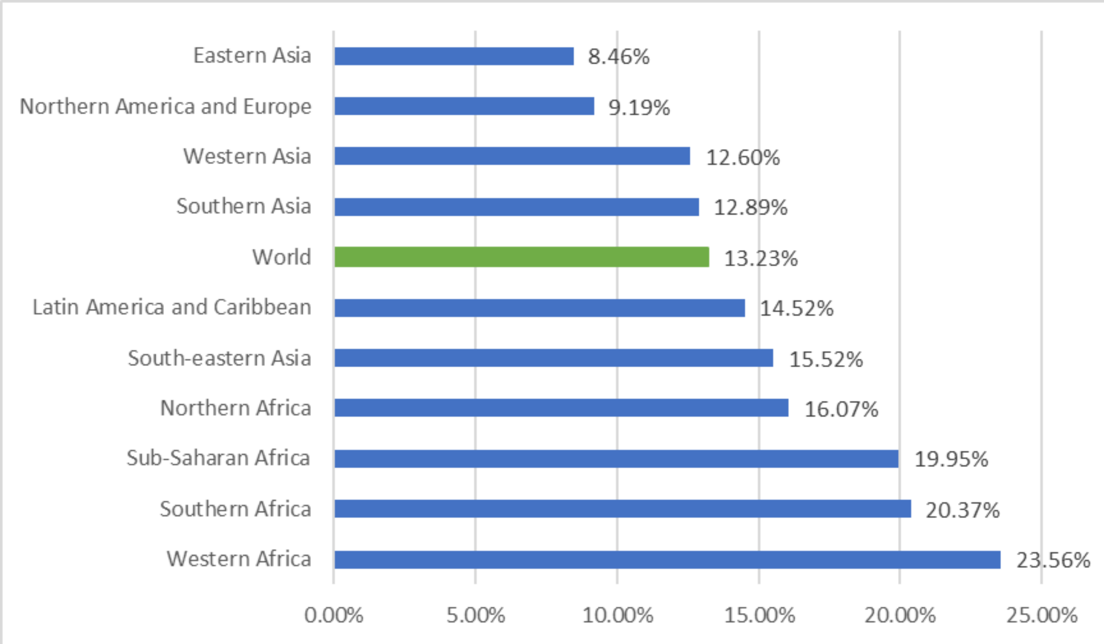

Fig. 1 | Share of post-harvest losses (PHL) by region in 2021. Source: Ritchie et al., (2022).

PHL have significant environmental and socioeconomic repercussions, mirroring the broader impacts associated with food loss and waste (FLW). When food is lost during post-harvest stages, essential natural resources, including land, water, and energy, are squandered without fulfilling their intended purpose of nourishing people [6-12]. Contemporary research reveals that FLW contributes 8% of worldwide greenhouse gas emissions, with 30% of cultivable land dedicated to producing food that ultimately goes unconsumed [1,13]. At 4.4 gigatons of CO2 emissions annually, food loss and waste ranks as the third-largest global emitter [14], trailing only China and the United States. Multiple studies have documented the environmental consequences of FLW, including its contribution to greenhouse gas emissions, soil degradation, and water resource depletion [15-20].

PHL induce severe social repercussions, exacerbating food insecurity primarily caused by economic distress, environmental degradation, regional conflicts and the recent COVID-19 pandemic. Approximately 1/3 of annual global food production ends up being wasted, and over 670 million people are undernourished, simultaneously [17,21]. In 2050, according to United Nations data, the world population will increase to close to 10 billion people, with this increase indicating an even greater pressure on agri-food systems. Reducing the FLW problem can yield 60-100% more available food for consumption, and this could be an important element in ensuring food consumption for all [22]. Therefore, the search for efficient food production practices is not the only way to meet the world's nutritional needs in the future, as the reduction of PHL can be part of the solution.

Moreover, FLW has economic implications for all parties involved in the food supply chain, affecting farmers, processors, distributors and ultimately consumers [23-24]. At every stage of the food supply chain, food loss means financial loss, increased production and management costs, and reduced purchasing power for consumers. According to estimates by the FAO, the economic losses associated with food waste and losses exceed $1 trillion annually globally [25]. In particular, the economic costs of PHL are severe for smallholder farmers, who often operate with marginal profits and limited access to markets and storage infrastructure [26]. In addition, the costs associated with managing waste from spoiled or unfit food add further economic burdens to all parties involved in the supply chain, such as processors and distributors.

Reducing PHL is highly linked to the achievement of several SDGs through enhancing food security, economic sustainability and environmental protection [23]. Reducing PHL supports SDG 2 (Zero Hunger), increasing food availability without requiring further expansion of agricultural production. At the same time, it directly contributes to SDG 12 (Responsible Consumption and Production), reducing waste and improving the efficiency of the food supply chain. In addition, the environmental benefits of reducing PHL are closely linked to SDG 13 (Climate Action), as avoiding unnecessary production leads to reduced greenhouse gas emissions [27]. Simultaneously, saving natural resources and reducing the need for deforestation for new crop areas contribute to achieving SDG 15 (Life on Land). At a socio-economic level, reducing losses can increase the disposable income of smallholder farmers, contributing to SDG 1 (No Poverty), while improving nutritional quality and access to nutritious food, enhancing SDG 3 (Good Health and Well-being) [26].

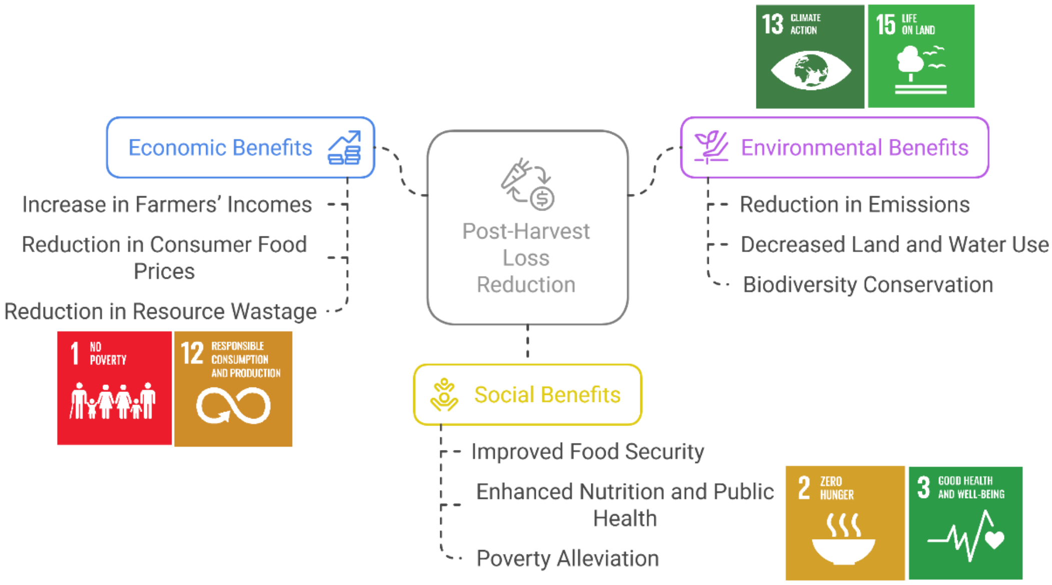

Fig. 2 | Socioeconomic and environmental benefits of post-harvest loss (PHL) reduction. Source: Author's elaboration.

The FABLE (Food, Agriculture, Biodiversity, Land-Use, and Energy) Calculator, developed by the FABLE Consortium, offers a science-based decision support system designed to analyze and simulate food system dynamics. The calculator includes 88 raw and processed indicators related to the agricultural sector, economy, and population [28]. A FABLE Pathway represents a combination of scenarios based on assumptions about key economic, institutional, climatic, and social variables. In turn, the scenarios encompass all of the possible actions that determine the trajectory of the chosen pathway by integrating agricultural data, land-use information, food demand, and environmental constraints, the FABLE Calculator enables users to model national and global food systems and assess the outcomes of various policy and practice scenarios.

The FABLE Calculator monitors losses across all different stages of the food supply chain, integrating scenarios on two distinct categories when developing national agri-food pathways [28]. Incorporating assumptions on PHL refers to the portion of crop and livestock products that is lost after being harvested but before reaching consumers. This loss is calculated as a percentage of total availability (production + imports + stock withdrawals). The percentage of PHL can vary over time based on the selected scenario. Following FAO guidelines, this definition focuses primarily on losses which occur during storage and transportation, excludes pre-harvest and harvest losses, accounts for processing losses in conversion rates, and distinguishes from household food waste.

Minimizing PHL is critical for reducing greenhouse gas emissions and adapting to climate change, but also for addressing problems such as food insecurity and poverty. In Greece, there is a significant lack of data on the quantities of PHL and on the possible solutions and compensations for reducing the problem. However, regional estimates suggest that PHL in the country may reach 30–40% for fruits and vegetables, and 8–10% for cereals, aligning with broader Mediterranean trends [17,29]. Although in the last decade, in the literature we find several studies on the problem of food waste with emphasis on the final stage of consumption and consumer behavior [30-32], the study of food loss is still at an early stage. For this reason, one of the main objectives of this study is to contribute to the discussion on the problem of food loss, highlighting the benefits of reducing the problem at an environmental and socio-economic level.

The paper is structured as follows. Section 2 introduces the methodology used to project the different pathways analyzed in relation to PHL reductions, with a focus on the FABLE Calculator and its underlying mechanisms. In Section 3, results of these pathways are illustrated through three key outcomes: targeted and feasible production, production costs, and GHG emissions. Section 4 discusses these results and outlines the related policy conclusions and implications. Lastly, Section 5 highlights the limitations of this study and the FABLE Calculator.

2. Methodology

The FABLE Calculator has been used to determine the potential socioeconomic and environmental impact of PHL reduction in Greece. The Calculator is an accounting tool designed by the FABLE Consortium[1] that builds on twenty-two different scenarios that can combine in more than a billion potential pathways. The model allows the user to simulate long-term agricultural pathways by monitoring the effects on GHG emissions, land-use changes, food consumption and agricultural production. For the aim of this study, the FABLE Calculator helped us to determine the medium- and long-term effects of a reduction in PHL in Greece over the period 2025-2050, by considering national targets and EU climate and food security objectives.

For the aim of the research, four different scenarios have been developed:

The first pathway monitors current trends to which no new policies are implemented and existing patterns in agricultural production and economic activity continue unchanged. In particular, this pathway includes trends such as high urbanisation, increased economic activity, stable dietary consumption patterns for the general population, a 50% rise in key exports, and increased reliance on food imports. Additionally, we assume no substantial shift in biofuel demand, no afforestation target, and no change in PHL [33].

The second and third pathways maintain the current trends for all parameters across 21 scenarios, except for PHL. In these two cases, we assume a reduction in PHL by 25% and 50%, respectively, to analyse the environmental and socio-economic impacts of improvements just in this single aspect. The choice of these targets is aligned with global ambitions outlined in some policy frameworks, such as the FAO's Global Initiative on Food Loss and Waste Reduction[2] and the SDG 12.3[3]. In particular, the SDG has the aim of halving per capita global food waste and substantially reducing food losses along production and supply chains by 2030. We proposed a 25% reduction in PHL that reflects a realistic policy benchmark, particularly because such a target can be considered more feasible in contexts with limited data availability, such as the case of Greece where reliable estimates of PHL are scarce; and a 50% reduction that constitutes a more ambitious mitigation scenario. The relevance of this target has also been highlighted in the literature. Flanagan et al. (2019) demonstrate that achieving a 50% reduction in current food loss and waste rates by 2050 would yield three critical benefits [34]. First, this reduction would bridge over 20% of the projected gap between food demand in 2050 and the food supply available in 2010. Second, it would eliminate the need to convert natural ecosystems and forests into agricultural land. Third, it would reduce greenhouse gas emissions by 1.5 GtCO2e annually by 2050.

The other two pathways embed the 25% and 50% drop in PHL into the"National Commitments" (NC) pathway. The development of a NC pathway is compliant with the FABLE Scenathon procedure[4]., whereby country teams determine the trajectory for food and land systems in alignment with national strategies, legal commitments and national and international environmental targets [35]. The Greek NC pathway used in this paper incorporates specific numerical and qualitative targets that were drawn from Greece's National Energy and Climate Plan (NECP), the Pissardies Committee Plan for the Greek Economy, and other national commitments aligned with EU-level goals. In particular, this pathway entails a medium to high-speed economic growth, a dietary shift toward healthier consumption patterns, as the one recommended by the EAT-Lancet Committee, and a reduction in imports. Other scenarios that were considered are: an increase of 50% in exports, reflecting the country's aim for outward-oriented economic growth, and a rise in productivity both for crops and livestock production. Moreover, it considers a reduction of 50% in PHLs and an increase in agricultural land under organic farming practices [35].

Based on the results from the FABLE Calculator, this paper concentrates on three key output metrics. Firstly, is analysed agricultural production (both targeted and feasible). We refer to targeted production as the production that a country aims to produce in order to meet the demand, and to feasible production as the maximum level of output that can be realized under land and productivity constraints. The other metrics considered in the discussion are: production costs and GHG emissions. All these dimensions are particularly relevant in light of existing literature, which underscores the critical role of reducing PHL as

---

[1] https://fableconsortium.org/

[2] https://www.fao.org/platform-food-loss-waste/en

[3] https://sdgs.un.org/goals/goal12

[4] "Scenathon stands for 'a marathon of scenarios' and refers to an iterative process used by FABLE to compare and align national pathways with the SDGs and planetary boundaries" (FABLE, 2024)

a key strategy for decreasing agricultural emissions. As highlighted by Raiser et al. (2023), minimizing food losses is essential not only to reach environmental sustainability but also to ensure that the food produced effectively reaches final consumers, enhancing food system efficiency [36]. In this light, the FABLE Calculator enables us to simulate how different percentages of PHL reduction can lead to a decrease in overall production needs while maintaining the same level of final consumption. In turn, this can reduce production costs and associated GHG emissions. Furthermore, changes in production levels and input requirements are likely to influence a broader set of socio-economic variables, including land use, input demand, and other economic indicators that will lead to a more sustainable farming system [17]. Hence, focusing on these correlated outcomes will allow us to assess both environmental and socio-economic consequences and trade-offs when pursuing PHL reduction strategies.

After running the results, we choose to include in the main graphs and analysis only the scenarios comparing CT with a 25% reduction in PHL (PHL-25%) and the NC pathway under the same reduction level (NC-25%). The two additional scenarios, which assume a 50% reduction in PHL (PHL-50%; NC-50%), are presented separately in Annex C, where their outcomes are briefly discussed. This decision was based on the fact that the differences between the 25% and 50% reduction scenarios were relatively minor. Further details will be provided in the 'Results' section.

3. Results

3.1. Production

The starting point of our analysis is the total agricultural production value based on producer prices from FAOSTAT, which are used to generate future production value (up to 2050). At constant prices, changes in production value over time result from two factors: variations in the quantities produced and shifts in the mix of goods and services being produced. This analysis reveals two key measures: targeted production values, representing what a country plans to produce, and feasible production values, representing what the country can realistically achieve given its constraints. [28].

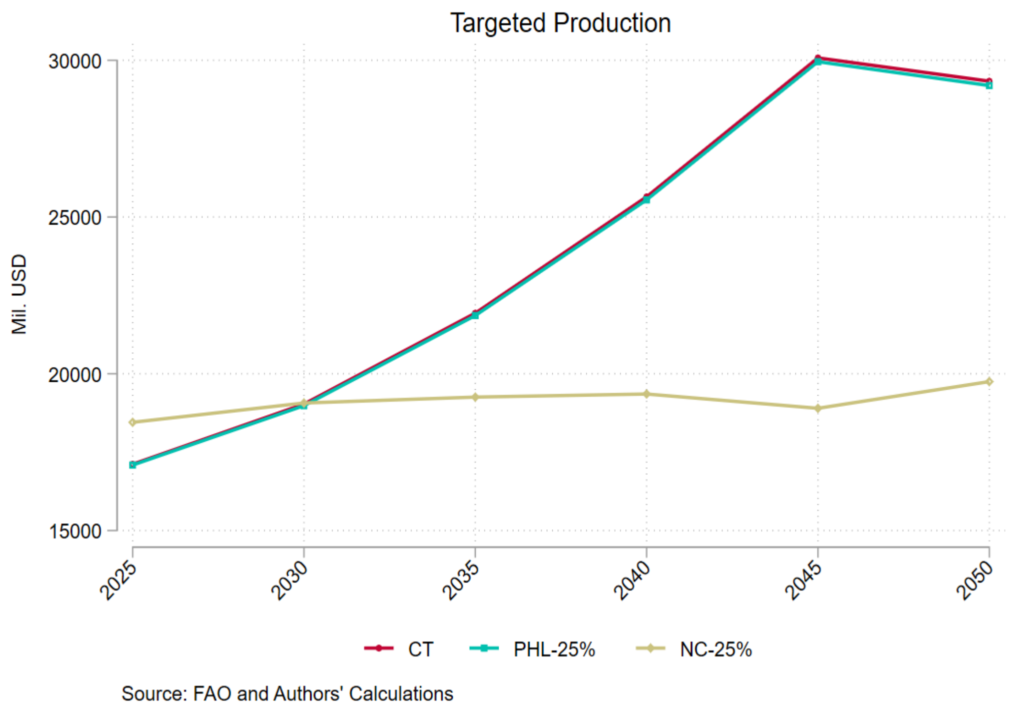

Fig. 3 | Evolution of targeted production under alternative scenarios. Source: FAO and authors' elaboration using FABLE Calculator (2024). The figure was created using Stata software.

Figure 3 shows the evolution of targeted production for three pathways: CT, PHL-25%, and NC-25%. Across all three scenarios, production increases over time, albeit with different trends. CT and PHL-25% follow the same trajectory, but when a PHL reduction measure is introduced, the amount of targeted production decreases over time, and the growth rate slightly slows. This outcome reflects a greater supply chain efficiency: with fewer losses, less gross production is needed to meet the same level of final demand, as a larger share of output successfully reaches the consumers. However, the positive trend is due to the fact that the demand for food, feed, and processing continues to rise over time because in these scenarios, it is considered a high rate of population growth and a continuity with the actual dietary pattern.

As a result, total targeted production still needs to increase, but more moderately, thanks to lower losses along the supply chain.

On the other hand, the NC-25% pathway displays substantially different trajectories for targeted production, showing a flatter trend compared to CT and PHL-25%. In Fig.3, NC-25% shows only a slight increase in targeted production from 2025 to 2050, at much lower levels than the CT and PHL cases. This difference is mainly driven by the NC strategy's broader policy framework, which not only targets a reduction in PHL by 25% but also incorporates complementary demand-side interventions. These include changes in diets, reduction in food overconsumption, and sustainable agricultural practices. Notably, the most influential of these is the adoption of the EAT-Lancet Commission's Planetary Health Diet[5], which is integrated into the NC pathway. This dietary shift is associated with significantly lower average caloric intake and a greater emphasis on plant-based foods, thereby reducing the overall food demand. As a result, the overall pressure on the agricultural system is reduced, leading to more stable production targets over time.

We outline the case of a 25% reduction in PHL because, interestingly, the gap between NC-25% and NC-50% is minimal[6], indicating that further PHL reduction under 25% contributes only marginally to additional production savings within the NC framework. This suggests diminishing returns to deeper loss reductions when embedded in a comprehensive strategy that already addresses systemic inefficiencies. The performance of the NC pathways underscores the importance of integrated approaches: while PHL reduction alone improves supply chain efficiency, combining it with ambitious national policy commitments on consumption has a far greater effect in stabilizing long-term production needs.

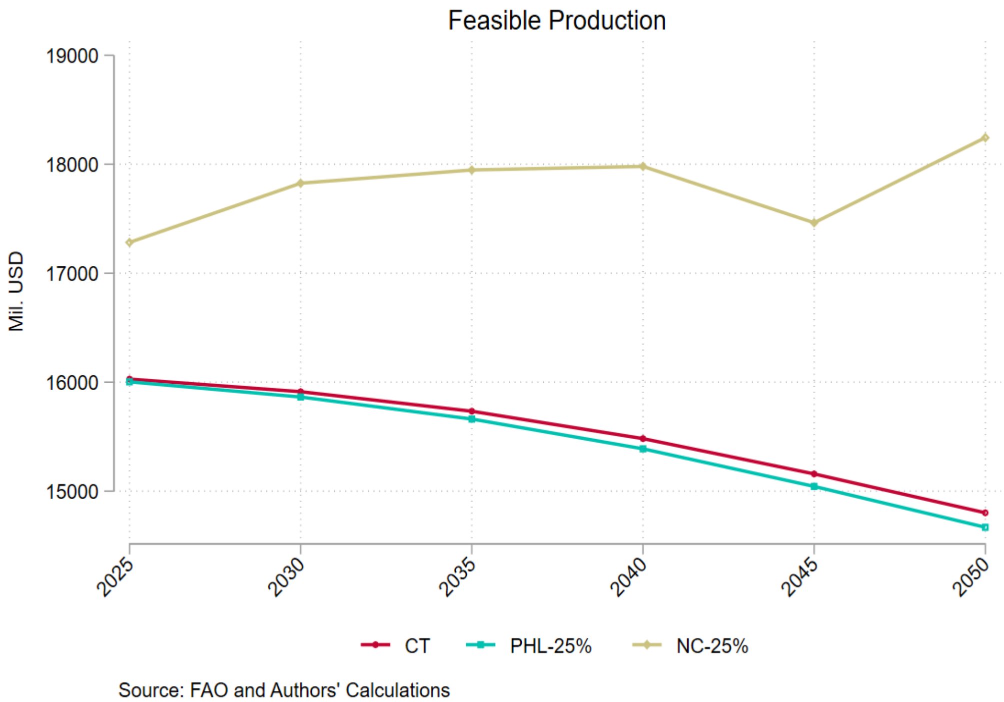

Fig. 4 | Evolution of feasible agricultural production under different PHL and NC scenarios. Source: FAO and authors' elaboration using FABLE Calculator (2024). The figure was created using Stata software.

While the reduction of PHL improves supply chain efficiency and reduces the need for gross production to meet a given level of final demand, the FABLE Calculator simulates an additional effect on the supply side. In the FABLE Calculator, feasible production is computed as a function of planted area, yield, and the average number of harvests per year. It reflects the maximum level of output that can be realized under land and productivity constraints, and is not directly determined by demand. In particular, CT and PHL-25% scenarios result in a decline in feasible production, which reflects the maximum level of agricultural output that can be achieved given land availability and productivity constraints. When considering CT, where PHL rate remain constant at 2010 levels, there is a gradual decline in feasible production over time because of structural dynamics such as the intensification of

[5] https://eatforum.org/eat-lancet-commission/the-planetary-health-diet-and-you/

[6] See Annex C.1

land-use constraints over time: there is a pressure from afforestation targets, urban expansion and protected areas, and even without any reduction in PHL, the area available from cropland and pasture shrinks over time. Feasible production reflects this declining availability of productive land, even if the demand-side and the related targeted production keep increasing. When we introduce a 25% reduction of PHL by 2050, feasible production declines even more compared to CT. The main reason is that the PHL reduction makes the agricultural system more efficient, where less gross production is required to meet the same net demand. The model interprets this reduced need as an opportunity to further reduce cropland area. Since fewer hectares are needed to achieve the required production (thanks to lower losses), the model deliberately releases agricultural land for other uses. The model does not reinvest efficiency gains into maintaining production levels but instead interprets them as an opportunity for land sparing. Consequently, feasible cropland contracts further, and with it, feasible production declines more steeply than in the CT scenario. This dynamic is embedded in the FABLE Calculator's structure, where land-use balance is enforced and competing claims on land intensify over time.

In contrast to the steady decline observed under CT and PHL-25%, feasible production under NC-25% follows an upward trajectory over time, reaching the highest values by 2050. This reflects the integrated nature of the National Commitments strategy, which not only improves supply chain efficiency through PHL reduction but also implements complementary policies that shape demand. As a result, the model allocates more land and resources to agricultural production, allowing feasible output to grow over time rather than contract. Moreover, the gap between feasible and targeted production remains relatively narrow and stable in the NC pathway, unlike the widening gap observed in CT and PHL-25% cases. This highlights that addressing PHL alone, while important, is not sufficient: effective food system transformation requires coordinated action on both the supply and demand sides.

3.2. Production Costs

Production costs are analysed through two separate figures. Fig. 5 displays the total costs of production in all the scenarios, while Fig. 6 breaks these costs down by component, specifically considering labor, pesticides, machinery, diesel, and fertilizers for all three pathways.

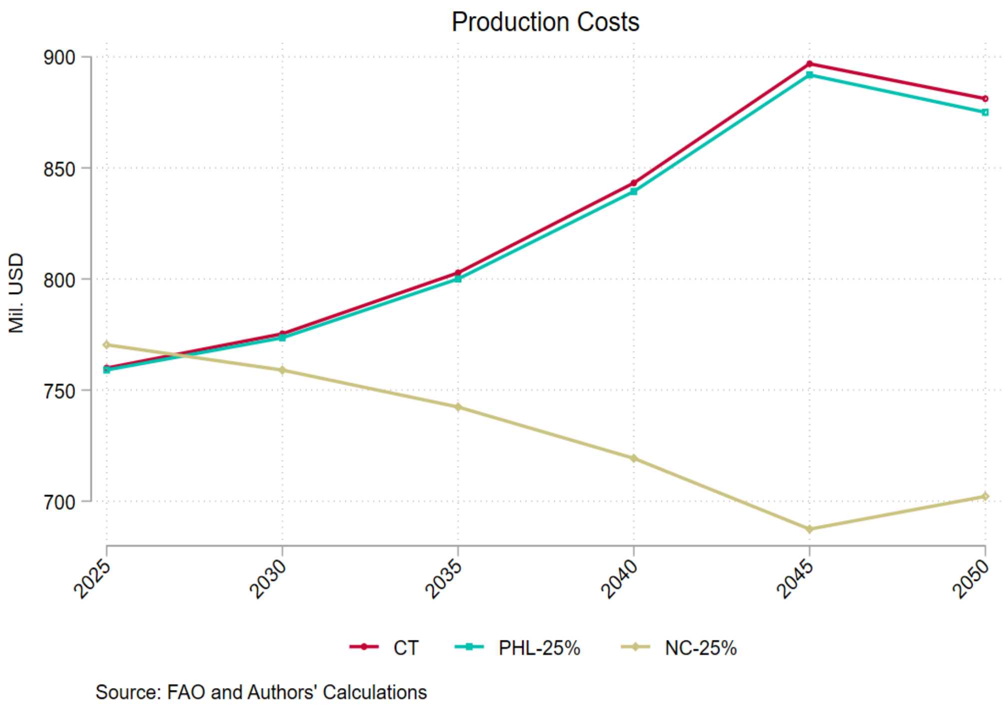

Fig. 5 | Evolution of agricultural production costs across scenarios. Source: FAO and authors' elaboration using FABLE Calculator (2024). The figure was created using Stata software.

When we consider the three scenarios shown in Fig. 5, we note that production costs increase steadily for CT and PHL-25%. In the CT scenario, costs rise from approximately USD 760 million in 2025 to over USD 880 million by 2050, reflecting the rising volume of targeted production required to meet growing food, feed, and processing demand. Although the PHL-25% scenario maintains the same structural dynamics, it shows moderately lower cost levels throughout the period. By 2050, production costs reach USD 875 million in the PHL-25% scenario, compared to USD 881 million under CT. This slight decline is a consequence of improved supply chain efficiency: less gross production is required to meet the same level of final demand, which in turn reduces resource use and associated expenditures.

As is the casefor targeted and feasible production, the cost-saving effect of more ambitious PHL targets is relatively limited, suggesting diminishing marginal gains from deeper loss reductions when not accompanied by broader systemic changes[7]. Overall, the upward trend in production costs persists across both scenarios due to the continued expansion in production volumes and input requirements, reinforcing that PHL reduction alone, while beneficial, cannot fully offset the structural cost pressures.

In stark contrast to the CT and PHL-25% scenarios, the NC-25% pathway exhibits a consistent decline in production costs over time. Costs fall from around USD 770 million in 2025 to approximately USD 702 million by 2045, before experiencing a modest rebound in 2050. This downward trend directly reflects the NC strategy's dual approach: not only does it incorporate PHL reductions, but it also implements demand-side policies that reduce overall food consumption needs through dietary changes and sustainable agricultural practices. As a result, both targeted and feasible production costs remain significantly lower in the NC scenario compared to the CT and PHL reduction-only pathways, which helps reduce input use, land demand, and associated production costs. However, this sharp cost reduction should not be attributed solely to lower production levels. It also depends on several key assumptions embedded in the NC pathway, such as high crop and livestock productivity, advances in organic agricultural practices, and the expansion of protected areas. These factors work together to further reduce production costs beyond what would be expected from demand-side changes alone.

The slight cost difference between NC-25% and NC-50%—with the latter achieving marginally lower values—suggests that while additional PHL reductions still bring efficiency gains, most of the cost-saving impact is already captured at the 25% reduction level when embedded in a comprehensive policy framework[8]. These findings highlight that integrated strategies that act on both supply and demand are essential not only to stabilize production levels but also to contain long-term production expenditures.

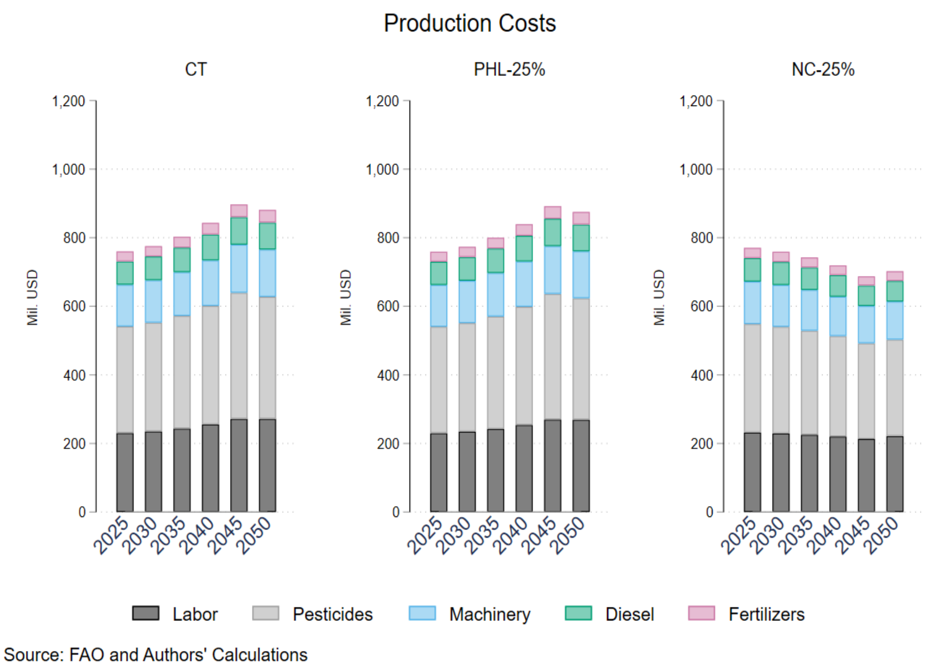

Fig. 6 | Breakdown of agricultural production costs by component across scenarios. Source: FAO and authors' elaboration using FABLE Calculator (2024). The figure was created using Stata software.

The disaggregated cost structure reveals distinct trends across inputs and scenarios. Across all pathways, labor and pesticides consistently represent the largest cost components, with labor contributing approximately one-third to the total production costs and pesticides accounting for a similarly large share. Under the CT scenario, both components increase significantly over time, with labor costs rising from USD 230.5 million in 2025 to nearly USD 272 million by 2050, and pesticide costs growing from approximately USD 310 million to USD 355 million. These increases reflect the rising demand for production inputs associated with higher output levels and unchanged agricultural practices.

---

[7] See Annex C.2

[8] See Annex C.2

In contrast, the PHL-25% scenario displays a slower increase in most input costs. For example, labor costs reach about USD 269 million in 2050—still increasing, but less steeply than in CT—while pesticide costs are also marginally lower than their CT counterparts. This moderation in cost growth reflects improved supply chain efficiency, which reduces the need for gross production and, consequently, input use.

The NC scenario diverges more substantially. The NC-25% pathway shows a clear downward trend in input costs over time across all components. Labor costs drop from around USD 232 million in 2025 to roughly USD 221 million (NC-25%). Pesticide expenditures fall even more significantly, from over USD 316 million in 2025 to approximately USD 281 million by 2050. Similar reductions are seen in machinery, diesel, and fertilizer costs. These declines reflect the effects of reduced targeted production resulting from the combined implementation of PHL reduction and demand-side interventions.

Overall, this analysis shows that while PHL reduction alone moderates the rise in input costs, only the NC strategy succeeds in reversing the trend, confirming that integrated policy approaches are necessary to contain agricultural expenditures in the long run.

3.3. GHG Emissions

The GHG emissions estimated by the FABLE Calculator are expressed in million tonnes of CO_2 equivalent ($MtCO_2e$) per year, based on five-year time steps. These emissions are grouped into three main categories: emissions from crops, emissions from livestock, and net emissions from land-use change (LUC).

Emissions from crop production are calculated from three sources: methane emissions resulting from rice cultivation, nitrous oxide emissions from the application of synthetic fertilizers, and emissions associated with energy use in agricultural fields. For livestock, the Calculator captures emissions from enteric fermentation in ruminants, which produce methane, as well as methane and nitrogen emissions generated from manure.

LUC emissions include both carbon sequestration and emission processes. Carbon sequestration occurs through afforestation and the abandonment of agricultural land, both of which lead to an increase in carbon stocks. Conversely, emissions arise when cropland, pasture, or urban areas expand into forests or other types of natural land, resulting in the loss of stored carbon. These emissions are calculated based on the difference in carbon stocks per hectare between the land cover type before and after the transition. In other words, emissions from LUC reflect the net change in carbon storage due to the conversion of land [28].

Before presenting the FABLE results, it is important to contextualize them within the historical dynamic of GHG emissions in Greece. In particular, the National Inventory Report of Greece for Greenhouse and Other Gases for the Years 1990-2021, from the Greek Ministry of Environment and Energy, highlights how agricultural emissions in Greece, particularly from N2O from soils, have shown a significant year-to-year variability, driven mostly by fluctuations in agricultural output and the use of synthetic fertilizers. Nevertheless, emissions from the sector accounted for 10.38% of total emissions in 2021, showing a decrease of approximately 22.60% compared to 1990 levels. Emissions reduction is mainly due to the reduction of N2O emissions from agricultural soils, because of the reduction in the use of synthetic nitrogen fertilizers and animal population. Moreover, agriculture continues to be a major source of methane (CH4) emissions, underscoring the sector's environmental impact and the need for targeted mitigation strategies [37].

In contrast, the Land Use, Land Use Change, and Forestry (LULUCF) sector acted as a net carbon sink over the same period, with its sequestration capacity increasing over time. Forest land, in particular, plays a critical role, with net removals rising from -1.23 Mt CO_2 eq in 1990 to -2.26 Mt CO_2 eq in 2021, primarily due to reduced logging activity and continued forest growth [37].

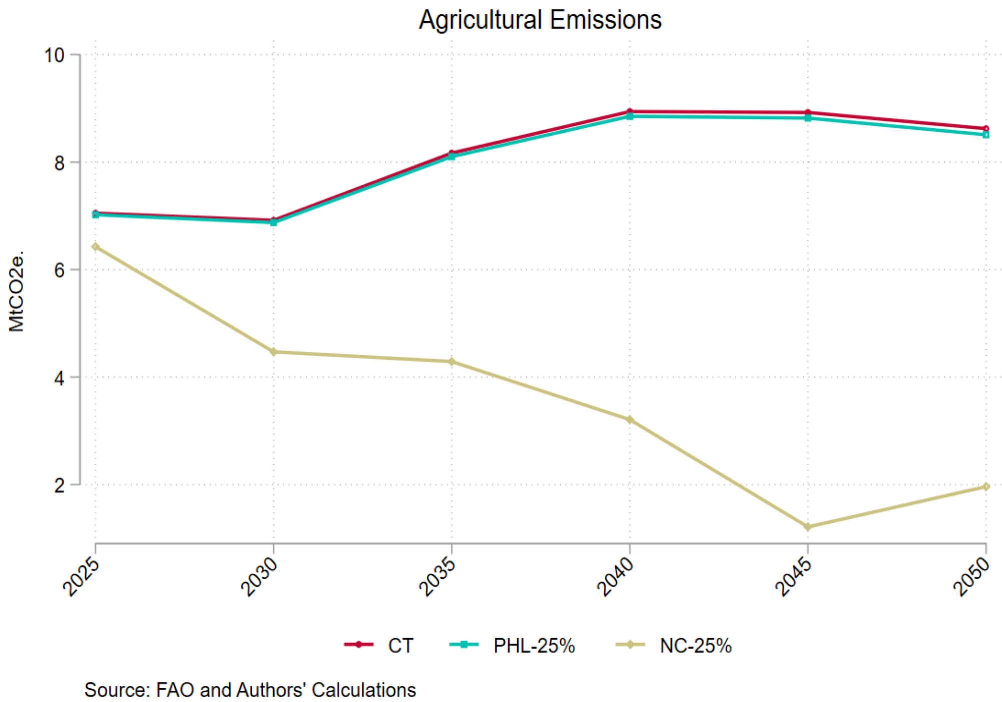

Fig. 7 | Evolution of agricultural greenhouse gas (GHG) emissions across policy scenarios. Source: FAO and authors' elaboration using FABLE Calculator (2024). The figure was created using Stata software.

The trajectory of total agricultural GHG emissions highlights the contrast between supply-side improvements alone and more integrated strategies. In the CT scenario, emissions increase from 7.05 $MtCO_2e$ in 2025 to a peak of 8.92 $MtCO_2e$ in 2045, before slightly declining to 8.62 $MtCO_2e$ by 2050. A similar pattern is observed in the PHL-25% scenario: while reducing PHL by 25% does slightly moderate emissions, total values in 2050 remain high, 8.51 $MtCO_2e$. These scenarios thus succeed in slowing emission growth but not in reversing it.

In sharp contrast, the NC pathway achieves a sustained and dramatic reduction in total emissions. Under NC-25%, emissions fall from 6.43 $MtCO_2e$ in 2025 to just 1.96 $MtCO_2e$ by 2050. This steep decline reflects the cumulative effect of PHL reduction combined with demand-side policies such as dietary shifts and reductions in livestock consumption. These findings confirm that while PHL reduction is beneficial for efficiency, it is the integration with broader systemic interventions—as in the NC scenario—that enables deep decarbonization of the agricultural sector.

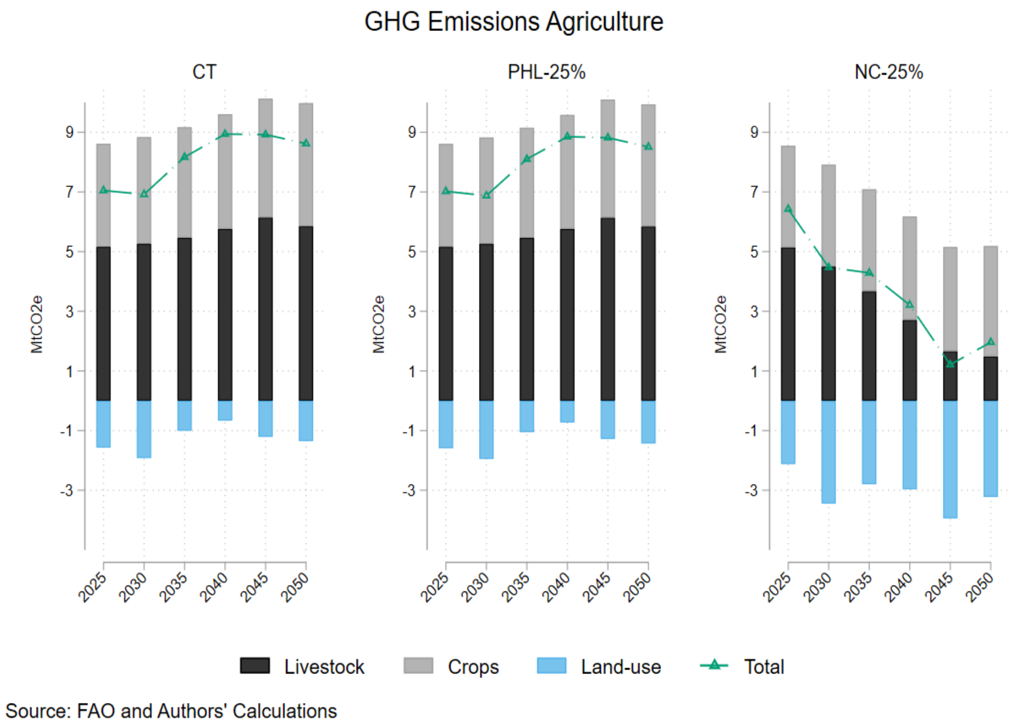

Fig. 8 | Agricultural greenhouse gas (GHG) emissions by sector under different scenarios. Source: FAO and authors' elaboration using FABLE Calculator (2024). The figure was created using Stata software.

Breaking down emissions by source reveals distinct dynamics. In the CT scenario, livestock remains the dominant source, rising from 5.2 $MtCO_2e$ in 2025 to over 6.1 $MtCO_2e$ in 2045. Crop-related emissions also grow, from 3.5 to 4 $MtCO_2e$ over the same period. Introducing PHL reduction slightly curbs both livestock and crop emissions—especially by reducing the need for overproduction—but the effects remain modest. However, in the NC scenario, both components decline markedly. Livestock emissions in NC-25% fall to 1.5 $MtCO_2e$ by 2050, and crop emissions stabilize around 3.7 $MtCO_2e$. This reflects how demand-side measures in the NC scenario contribute to reducing livestock numbers and input use. PHL reduction alone primarily impacts the efficiency of the supply chain, whereas NC strategies affect both production volume and structure, particularly in livestock systems.

4. Discussion and Conclusions

PHL are a major obstacle to ensuring global food security and environmental sustainability [38], yet there are few studies and a lack of data on the importance of their reduction for the environment, society and the economy [2]. The main goal of this study is to highlight the importance of PHL reduction in achieving the transition to a more sustainable, resilient and climate-neutral agri-food system. The analysis carried out using the FABLE Calculator shows the multiple impacts of reducing losses in terms of production, costs and GHG emissions, and simultaneously allows comparisons between the different policy scenarios and levels of intervention.

The interpretation of the results leads to some important conclusions. Specifically, reducing PHL, even at the level of 25%, slightly reduces production cost and partly contributes to the reduction of GHG emissions. These benefits are achieved without compromising the nutritional coverage of the population, as final consumption remains stable. This is a particularly important element given that food loss severely affects nutrient-rich foods such as fruits, vegetables and fish [39]. The production cost savings under PHL-25% are modest (~0.7%), but they are present across all major input categories—pesticides, fertilizers, and labor. These findings are consistent with international evidence that PHL reduction offers a low-cost, high-impact strategy for improving food availability and supply chain performance [34,40]. However, it is observed that the transition from 25% to 50% reduction in losses is accompanied by relatively limited additional benefits[9]. This phenomenon of diminishing returns suggests that a significant part of the environmental and economic gains can already be achieved with targeted and realistic interventions, making the relevant policies accessible and immediately applicable.

[9] See Annex C

At the same time, our modeling projections reveal that feasible production declines in the PHL-25% scenario, as land previously used for surplus production is reallocated toward reforestation, biodiversity or less intensive uses—highlighting an important positive externality of efficiency gains.

The greatest benefit, however, is recorded in the comprehensive NC scenario, which is not limited to reducing PHL but also includes a series of broader structural changes. The combination of increased productivity, healthier eating habits [41,42], import restrictions, export reinforcement and a shift to environmentally friendly practices creates a multidimensional intervention model that strengthens the country's productive capacity, drastically reduces emissions, and contributes to carbon sequestration through land-use changes. This approach highlights the importance of coordinated policymaking, where supply and demand interventions operate in tandem rather than separately.

In terms of environmental outcomes, GHG emissions decline slightly under PHL-25%, but only the NC-25% achieves substantial reductions, falling to just 1.96 $MtCO_2e$ in 2050 compared to 6.4 $MtCO_2e$ in the baseline. This reduction is driven not only by lower food loss but by structural changes in diets, land use, and trade. These findings are aligned with global mitigation potential estimates. According to the World Resources Institute, halving global food loss and waste by 2050 could reduce greenhouse gas emissions by 1.5 $GtCO_2e$ annually and close 20% of the global food availability gap [34].

The NC pathway also exhibits the highest economic efficiency, with production costs falling by more than 20% compared to the baseline. These scenarios strengthen national productive capacity while minimizing inputs and emissions, making them the most transformative option overall. Our simulation of reduction in PHL in Greece supports this global narrative, showing measurable gains in food system efficiency, cost savings, and emissions reductions. This reinforces the idea that national-level PHL interventions can scale up to generate meaningful global benefits.

Overall, our study findings have direct implications for national agri-food policy design, particularly for Mediterranean countries, where food systems face pressures from climate change, land degradation, resource scarcity, such as water, and strong socio-economic inequalities [43,44]. The demonstrated benefits of reducing PHL -especially in the NC scenario- highlight those sustainable transitions do not necessarily require radical changes in production volumes. These results support a case where food security, environmental protection, and economic sustainability are mutually reinforcing and not in competition.

From a policy perspective, these findings are directly relevant to the EU’s current strategic direction. The observed benefits of reducing PHL and improving resource efficiency support the priorities of the European Green Deal, the Farm to Fork Strategy, and the EU Biodiversity Strategy for 2030 [45-48]. This suggests that governments and institutions should prioritize reducing PHL as a central pillar of both climate action and food systems resilience strategies. Investments in FSC infrastructure, farmer education and better monitoring mechanisms can lead to measurable improvements in emissions, land use efficiency and input utilisation. Furthermore, our study results can help the design of multi-level interventions, linking local improvements in post-harvest management to national commitments to the Sustainable Development Goals – particularly SDGs 2, 12 and 13 [27]. Overall, the study highlights the importance of integrating PHL reduction policies into broader national strategies for climate change mitigation, sustainable production, and social equity.

Despite the positive findings, the implementation of such a strategy faces several obstacles. Economic constraints, such as the need for investments in storage and refrigeration infrastructure, constitute a key obstacle, especially for smaller farmers and cooperatives. Technological challenges concern access to appropriate equipment and the transmission of know-how, while political difficulties relate to the lack of an institutional framework and systematic recording of PHL in the country. In addition, the social dimensions of change, such as the adoption of new dietary patterns or the restructuring of production, may cause resistance that requires broader communication, education and social acceptance.

In order to utilize the benefits outlined in this study, it is critical to identify and implement concrete actions that can reduce PHL both globally and within the Greek context. International best practices emphasize investments in cold chain logistics, storage technologies, and improved transport infrastructure to mitigate losses, especially for perishable products [49-52]. Training programs for farmers and cooperatives on post-harvest handling, grading, and packaging are essential to reduce mechanical losses [53-56]. For Greece specifically, targeted interventions could include the modernization of regional agricultural cooperatives, the development of mobile storage and processing units in rural areas, and the integration of digital tools for logistics and supply chain monitoring. Establishing a national PHL monitoring framework and motivating short supply chains—especially for fruits and vegetables—could significantly reduce spoilage and improve economic returns for small producers [26]. These actions align with EU policy priorities under the Green Deal and Farm to Fork Strategy, and would support both national sustainability goals and broader SDG targets [45-48].

Taking the above into account, we can conclude that the reduction of PHL is not simply a "technical" improvement in the food supply chain, but a key element of an environmentally and economically sustainable agri-food strategy. Its implementation can support national and European climate goals, reduce pressure on natural resources and strengthen the self-sufficiency and resilience of the agri-food systems.

However, to fully realize the benefits, the reduction of PHL requires the integration of a broader political agenda. Creating a national framework for monitoring and recording losses, directing funding towards critical infrastructure, providing incentives for sustainable practices and strengthening cross-sectoral cooperation are necessary steps in this direction. Furthermore, the exploitation of these results - even they are referred to the case of Greece- can serve as a model for other countries, with similar economic characteristics and comparable agrifood systems.

In conclusion, as food systems face pressure from population growth, climate change, and resource limitations, reducing PHL arises as a strategic and necessary intervention. The FABLE Calculator is a reliable solution, enabling a holistic assessment having both medium and long-term abilities for planning. Through its results, policymakers -and broader the stakeholders of FSC- can make informed decisions that not only minimize losses but also enhance food and nutrition security, safeguard ecosystems, and promote sustainable agricultural development.

5. Limitations and future research

The strength of the Calculator mostly lies in its capacity to explore context-specific trade-offs and synergies by integrating multiple policy-relevant variables. It allows for transparent scenario customization and stakeholder engagement, making it particularly suitable for participatory policy design. As such, it can serve as a valuable tool for informing both national authorities and EU institutions about the implications of reducing PHL, thereby supporting the development of innovative strategies aligned with SDG 12.

Nevertheless, the study presents some limitations that should be mentioned. The FABLE Calculator is not an optimization model, meaning it does not account for price dynamics, cost-effectiveness pathways, and real-world behavioral feedback. Additionally, it does not explicitly model technical and economic feasibility, such as the costs associated with reducing PHL or limitations in storage and transport infrastructure. Also, the model assumes unlimited water availability and requires an understanding of its Excel-based architecture, which may limit accessibility for some users. This means that we cannot fully capture the economic or social feasibility of the strategies we modeled.

Additionally, the data selected for PHL levels in Greece are based on general estimates, as there is a lack of national data. Continuing, in the NC scenario, we assume changes in diets, production methods and trade patterns, but we do not assess how realistic or acceptable these changes were for farmers and other stakeholders. Finally, we do not include the investment costs required for infrastructure, training or new technologies.

Regarding future research, it should aim to solve the problem of the lack of data on food loss for each agri-food product in Greece. Meanwhile, the real cost of food loss reduction strategies should be studied, as well as the socio-economic factors that influence their success should be highlighted. Ultimately, the connection between the FABLE model and economic and behavioral models could provide a more comprehensive picture in the future.

References

1. FAO. *The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction*. FAO, Rome (2019).

2. Stathers T, Holcroft D, Kitinoja L, Mvumi BM, English A, Omotilewa O, Kocher M, Ault J, Torero M. A scoping review of interventions for crop postharvest loss reduction in sub-Saharan Africa and South Asia. *Nat Sustain* **3**, 821–835 (2020). https://doi.org/10.1038/s41893-020-00622-1

3. Ritchie H, Rosado P, Roser M. Environmental impacts of food production. *Our World in Data* (2022). https://ourworldindata.org/environmental-impacts-of-food

4. FAO. *Global food losses and food waste: Extent, causes and prevention*. Food and Agriculture Organization of the United Nations (2011). https://www.fao.org/3/mb060e/mb060e00.pdf

5. Michel M, Eldridge AL, Hartmann C, Klassen P, Ingram J, Meijer GW. Benefits and challenges of food processing in the context of food systems, value chains and sustainable development goals. *Trends Food Sci Technol* **153**, 104703 (2024). https://doi.org/10.1016/j.tifs.2024.104703

6. Hall KD, Guo J, Dore M, Chow CC. The progressive increase of food waste in America and its environmental impact. *PLoS One* **4**, e7940 (2009). https://doi.org/10.1371/journal.pone.0007940

7. Girotto F, Alibardi L, Cossu R. Food waste generation and industrial uses: A review. *Waste Manag* **45**, 32–41 (2015). https://doi.org/10.1016/j.wasman.2015.06.008

8. Willett W et al. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019). https://doi.org/10.1016/S0140-6736(18)31788-4

9. Iqbal MW, Kang Y, Jeon HW. Zero waste strategy for green supply chain management with minimization of energy consumption. *J Clean Prod* **245**, 118827 (2020). https://doi.org/10.1016/j.jclepro.2019.118827

10. Read QD et al. Assessing the environmental impacts of halving food loss and waste along the food supply chain. *Sci Total Environ* **712**, 136255 (2020). https://doi.org/10.1016/j.scitotenv.2019.136255

11. Luo N, Olsen TL, Liu Y. A conceptual framework to analyze food loss and waste within food supply chains: An operations management perspective. *Sustainability* **13**, 927 (2021). https://doi.org/10.3390/su13020927

12. Burlakovs J et al. On the way to 'zero waste' management: Recovery potential of elements, including rare earth elements, from fine fraction of waste. *J Clean Prod* **186**, 81–90 (2018). https://doi.org/10.3390/separations6020025

13. Principato L, Mattia G, Di Leo A, Pratesi CA. The household wasteful behaviour framework: A systematic review of consumer food waste. *Ind Mark Manag* **93**, 641–649 (2021). https://doi.org/10.1016/j.indmarman.2020.07.010

14. Jacob-John J, D'Souza C, Marjoribanks T, Singaraju S. Sustainable development practices for SDGs: A systematic review of food supply chains in developing economies. In: Nguyen N et al. (eds) *Environmental Sustainability in Emerging Markets*. Springer, Singapore (2022). https://doi.org/10.1007/978-981-19-2408-8_10

15. Schanes K, Dobernig K, Gozet B. Food waste matters–a systematic review of household food waste practices and their policy implications. *J Clean Prod* **182**, 978–991 (2018). https://doi.org/10.1016/j.jclepro.2018.02.030

16. Secondi L, Principato L, Laureti T. Household food waste behavior in EU-27 countries: A multilevel analysis. *Food Policy* **56**, 25–40 (2015). https://doi.org/10.1016/j.foodpol.2015.07.007

17. FAO, IFAD, UNICEF, WFP & WHO. *The State of Food Security and Nutrition in the World 2023*. FAO, Rome (2023). https://doi.org/10.4060/cc3017en

18. Chapagain A, James K. The water and carbon footprint of household food and drink waste in the UK. In: *Waste & Resources Action Programme (WRAP)*. WWF, UK (2011).

19. Quested TE, Parry AD, Easteal S, Swannell R. Food and drink waste from households in the UK. *Nutr Bull* **36**, 460–467 (2011). https://doi.org/10.1111/j.1467-3010.2011.01924.x

20. Parfitt J, Barthel M, Macnaughton S. Food waste within food supply chains: quantification and potential for change to 2050. *Philos Trans R Soc Lond B Biol Sci* **365**, 3065–3081 (2010). https://doi.org/10.1098/rstb.2010.0126

21. FAO, IFAD, UNICEF, WFP & WHO. *The State of Food Security and Nutrition in the World 2022*. FAO, Rome (2022). https://doi.org/10.4060/cc0639en

22. FAO. *The State of Food and Agriculture 2023 – Revealing the true cost of food to transform agrifood systems*. FAO, Rome (2023). https://doi.org/10.4060/cc7724en

23. Trevisan C, Formentini M, Pullman M. Innovators and transformers: Is wasted food just waste? Reconceptualising food loss and waste in operations and supply chain management research and practice. *Int J Phys Distrib Logist Manag* **55**, 361–375 (2025). https://doi.org/10.1108/IJPDLM-12-2023-0471

24. Muth MK et al. A systems approach to assessing environmental and economic effects of food loss and waste interventions in the United States. *Sci Total Environ* **685**, 1240–1254 (2019). https://doi.org/10.1016/j.scitotenv.2019.06.230

25. FAO. *Food wastage footprint: Full-cost accounting – Final report*. FAO, Rome (2014).

26. Touch V et al. Smallholder farmers' challenges and opportunities: Implications for agricultural production, environment and food security. *J Environ Manag* **370**, 122536 (2024). https://doi.org/10.1016/j.jenvman.2024.122536

27. Khan AA, Siddiqui Y, Siddique KHM et al. Minimizing postharvest food losses: a vital strategy to alleviate food insecurity and malnutrition in developing nations: a review. *Discov Food* **4**, 145 (2024). https://doi.org/10.1007/s44187-024-00129-0

28. Mosnier A et al. FABLE Calculator: 2020 update. IIASA and SDSN (2020). https://www.fableconsortium.org/

29. CIHEAM & FAO. Post-harvest losses and waste: A global overview. In: *Mediterra 2016 – Zero Waste in the Mediterranean: Natural Resources, Food and Knowledge*. CIHEAM & FAO, 195–212 (2016). https://www.iamm.ciheam.org/uploads/attachments/448/09_Mediterra2016_EN.pdf

30. Theodoridis P, Zacharatos T, Boukouvala V. Consumer behaviour and household food waste in Greece. *Br Food J* **126**, 965–994 (2024). https://doi.org/10.1108/BFJ-02-2023-0141

31. Zacharatos T, Theodoridis P. From plate to bin: Consumer segments and food waste in Greece. *Waste* **3**, 2 (2025). https://doi.org/10.3390/waste3010002

32. Zacharatos T, Theodoridis P. Consumer behaviour and food waste in Greece: Insights from 2012 to 2024. *Encyclopedia* **5**, 42 (2025). https://doi.org/10.3390/encyclopedia5020042

33. Koundouri P et al. FABLE Scenathon 2023: Pathways for food and land-use systems in Greece. SDSN (2024). https://www.fableconsortium.org/

34. Flanagan K, Robertson K, Hanson C. Reducing food loss and waste: Setting a global action agenda. World Resources Institute (2019). https://www.wri.org/research/reducing-food-loss-and-waste-setting-global-action-agenda

35. FABLE. Transforming food and land systems to achieve the SDGs. In: Sachs et al. (eds) *The Sustainable Development Report 2024*. SDSN, New York and Paris (2024).

36. Raiser K et al. Feeding a net-zero world: Background paper for the 44th Round Table on Sustainable Development. OECD (2023). https://www.oecd.org/environment/feeding-a-net-zero-world.pdf

37. Ministry of Environment and Energy. *National Inventory Report of Greece for Greenhouse and Other Gases for the Years 1990–2021*. Climate Change: Emissions Inventory. Ministry of Environment and Energy, Greece (2023).

38. Abbas H, Zhao L, Gong X et al. Environmental and economic influences of postharvest losses across the fish-food products supply chain in the developing regions. *Environ Dev Sustain* **26**, 28335–28366 (2024). https://doi.org/10.1007/s10668-023-03814-9

39**.** Kummu M et al. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Sci Total Environ* **438**, 477–489 (2012). https://doi.org/10.1016/j.scitotenv.2012.08.092

40. Ali A, Xia C, Ouattara N, Mahmood I, Faisal M. Economic and environmental consequences of postharvest loss across food supply chain in developing countries. *J Clean Prod* **323**, 129146 (2021). https://doi.org/10.1016/j.jclepro.2021.129146

41. Grummon AH, Lee CJ, Robinson TN, Rimm EB, Rose D. Simple dietary substitutions can reduce carbon footprints and improve dietary quality across diverse segments of the US population. *Nat Food* **4**, 966–977 (2023). https://doi.org/10.1038/s43016-023-00864-0

42. García S et al. Carbon dioxide emissions and adherence to Mediterranean diet in an adult population: the Mediterranean diet index as a pollution level index. *Environ Health* **22**, 1 (2023). https://doi.org/10.1186/s12940-022-00956-7

43. Ahmed F, Shakeel A, Ahmad S, Kaur N. Exploring the linkages between land degradation and food insecurity. *Asia Pac J Rural Dev* (2025). https://doi.org/10.1177/10185291241307272

44. Lionello P (ed). *The climate of the Mediterranean region: From the past to the future*. Elsevier, Amsterdam (2012). https://doi.org/10.1016/C2011-0-06210-5

45. Boix-Fayos C, De Vente J. Challenges and potential pathways towards sustainable agriculture within the European Green Deal. *Agric Syst* **207**, 103634 (2023). https://doi.org/10.1016/j.agsy.2023.103634

46. European Commission. *The European Green Deal*. COM(2019) 640 final (2019). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640

47. European Commission. *A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system*. COM(2020) 381 final (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0381

48. European Commission. *EU Biodiversity Strategy for 2030 – Bringing nature back into our lives*. COM(2020) 380 final (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0380

49. Mustafa MFM, Navaranjan N, Demirovic A. Food cold chain logistics and management: A review of current development and emerging trends. *J Agric Food Res* **18**, 101343 (2024). https://doi.org/10.1016/j.jafr.2024.101343

50. Chermala A, Acharya P, Singh RK. Cold chain logistics performance: a framework. *Meas Bus Excell* **29**, 55–75 (2025). https://doi.org/10.1108/MBE-11-2023-0174

51. Fatorachian H, Shokri A. Waste generation patterns and mitigation strategies in cold chains. *J Environ Manag* **380**, 125108 (2025). https://doi.org/10.1016/j.jenvman.2025.125108

52. Zhang B, Mohammad J. Sustainability of perishable food cold chain logistics: A systematic literature review. *SAGE Open* (2024). https://doi.org/10.1177/21582440241280455

53. Seshadri NM, Palanisamy AS, Mohanavelu T, McDermott O. Minimization of losses in postharvest of fresh produce supply chain. *J Agribus Dev Emerg Econ* (2024). https://doi.org/10.1108/JADEE-04-2024-0139

54. Parmar A, Hensel O, Sturm B. Post-harvest handling practices and associated food losses and limitations in the sweetpotato value chain of southern Ethiopia. *NJAS Wageningen J Life Sci* **80**, 65–74 (2017). https://doi.org/10.1016/j.njas.2016.12.002

55. Esguerra E, Rapusas R, Rolle RS. *Post-harvest management of lettuce to ensure quality and safety – Guidance for stakeholders in the horticultural supply chain*. FAO, Rome (2020).

56. Urugo MM et al. Addressing post-harvest losses through agro-processing for sustainable development in Ethiopia. *J Agric Food Res* **18**, 101316 (2024). https://doi.org/10.1016/j.jafr.2024.101316

Acknowledgements

The work carried out by author Ginevra Coletti for this paper was produced while attending the PhD programme in PhD in Sustainable Development And Climate Change at the University School for Advanced Studies IUSS Pavia, Cycle XXXIX, with the support of a scholarship financed by the Ministerial Decree no. 351 of 9th April 2022, based on the NRRP - funded by the European Union - NextGenerationEU - Mission 4 "Education and Research", Component 1 "Enhancement of the offer of educational services: from nurseries to universities" - Investment 4.1 "Extension of the number of research doctorates and innovative doctorates for public administration and cultural heritage."

Author Contributions

T.Z, G.C. and K.D: Conceptualization, Methodology, Analysis-articles reviewed, Writing-Original draft preparation, Review-editing. P.K:Conceptualization, Methodology, Writing–review-editing and supervision. All authors have read and approved the final manuscript**.**

Competing interests

The authors declare no competing interests**.**

Data availability

No primary datasets were generated, but meta-analyses were conducted using data compiled from primary data sources. The full dataset will be made available upon reasonable request. Requests for data should be addressed to F.Z. or K.D.

Annex A - Scenarios definition

#	Scenario	CT	PHL-25%	PHL-50%	NC-25%	NC-50%
0	*Calibration year*	2020				
1	*GDP*	"Middle of the road": Medium speed of economic growth			Sustainability - Medium high speed of economic growth	
2	*Population*	No change in fertility, mortality, replacement, and migration			Medium growth	
3	*Diets*	Same dietary pattern as in 2010			EAT-Lancet recommended diet (average values per food group)	
4	*Share of the food supply which is wasted*	Same share as in 2010			Reduced share compared to 2010 (10% for all product categories)	
5	*Share of consumption which is imported*	Stable			Reduced (50%)	
6	*Evolution of exports*	Exports multiplied by 1.5 by 2050			Exports multiplied by 2 by 2050	
7	*Livestock productivity*	Same productivity growth as over 2000-2010			Higher productivity than 2000-2010	
8	*Crop productivity*	Same productivity as in the calibration year			At least 80% closure of yield gap	
9	*Land available for agricultural expansion*	No deforestation beyond 2030				
10	*Afforestation*	No afforestation/reforestation target				
11	*Ruminant density*	No change				
12	*Trade adjustment to ensure a global trade balance*	Trade is fixed to the adjusted value				

#	Scenario	CT	PHL-25%	PHL-50%	NC-25%	NC-50%
13	*Level of activity of the population*	A moderately active lifestyle that includes physical activity equivalent to walking about 1.5 to 3 miles per day at 3 to 4 miles per hour, in addition to the activities of independent living.				
14	*Climate change*	Climate change impacts are not included				
15	*Protected areas expansion*	Same level of protected areas as in 2010 (33,4%)			Expansion of protected area by 11,6% to reach 50%	
16	***Post-harvest losses***	**Constant share of supply available lost during storage & transportation after 2010**	**Reduced share of supply available lost during storage and transportation compared to 2010 (25%)**	**Reduced share of supply available lost during storage and transportation (50%) compared to 2010**	**Reduced share of supply available lost during storage and transportation compared to 2010 (25%)**	**Reduced share of supply available lost during storage and transportation (50%) compared to 2010**
17	*Biofuel demand*	Stable biofuel demand as of 2010			Projections until 2028, stable afterwards	
18	*Evolution of prices*	Prices expressed in current terms (current dollar around the year 2020)			Prices under inflation change based on the average yearly CPI change in the 2000-2020 period	
19	*Global warming potential coefficient*	GWP from the Sixth Assessment Report				
20	*Urban area expansion*	Current Trend of urban land use change			Constant 2015 level of urban area	

#	Scenario	CT	PHL-25%	PHL-50%	NC-25%	NC-50%
21	*Agroecological practices*	Increase in share of cropland under diversified farming practices (various)			Increase in share of cropland under organic agriculture	
22	*Irrigated harvested area*	Same irrigated harvested area as in 2010			Low irrigated area expansion	

Table 1 | Pathways definition by each Scenario. Source: Authors' elaboration.

Annex B - Results' Data

B.1. Targeted and Feasible Production

TARGETED PRODUCTION (Mil. USD)					
	CT	**PHL-25%**	**PHL-50%**	**NC-25%**	**NC-50%**
2025	17114,08	17087,86	17061,86	18452,7109	18424,84
2030	19033,84	18982,54	18932,06	19066,941	19010,48
2035	21933,48	21858,12	21784,53	19256,459	19171,69
2040	25644,66	25546,23	25450,86	19354,2802	19242,25
2045	30074,81	29953,9	29837,66	18899,1235	18762,14
2050	29332,8	29192,94	29059,49	19750,3611	19583,21

Table 2 | Data results on Targeted Production (2025-2050). Mil. USD. Source: Authors' elaboration.

FEASIBLE PRODUCTION (Mil. USD)					
	CT	**PHL-25%**	**PHL-50%**	**NC-25%**	**NC-50%**
2025	16028,31	16003,49	15978,8623	17283,11	17256,74
2030	15912,81	15864,21	15816,4076	17826,24	17772,85
2035	15733,43	15661,95	15592,1993	17947,59	17867,46
2040	15482,03	15388,6	15298,1501	17980,1	17874,27

FEASIBLE PRODUCTION (Mil. USD)					
2045	15158,41	15043,53	14933,167	17463,86	17334,54
2050	14801,44	14668,5	14541,78	18244,52	18086,76

Table 3 | Data results on Feasible Production (2025-2050). Mil. USD. Source: Authors' elaboration

B.2. Production Costs

PRODUCTION COSTS (Mil. USD)					
	CT	**PHL-25%**	**PHL-50%**	**NC-25%**	**NC-50%**
2025	759,92	759,05	758,18	770,3891	769,50
2030	775,34	773,55	771,78	759,0132	757,22
2035	802,80	800,04	797,32	742,3819	739,71
2040	843,23	839,41	835,65	719,2763	715,81
2045	896,90	891,90	886,98	687,3944	683,28
2050	881,19	875,06	869,06	702,1552	696,90

Table 4 | *Data results on Production Costs (2025-2050). Mil. USD. Source: Authors' elaboration*

B.3. Total GHG Emissions

GHG EMISSIONS (MtCOe)					
	CT	**PHL-25%**	**PHL-50%**	**NC-25%**	**NC-50%**

2025	7,05	7,02	6,99	6,43	6,40
2030	6,92	6,88	6,83	4,47	4,44
2035	8,17	8,10	8,04	4,29	4,24
2040	8,94	8,85	8,77	3,21	3,14
2045	8,92	8,82	8,72	1,21	1,14
2050	8,62	8,51	8,40	1,96	1,87

Table 5 | Data results on Total GHG Agricultural Emissions (2025-2050). MtCO2e. Source: Authors' elaboration

Annex C - Results of Pathways Considering 50% PHL Reduction

In this annex, we include the outputs of the PHL-50% and NC-50% scenarios to compare them with their 25% counterparts. Since the differences in results are marginal and the 50% target is considered less feasible due to limited supporting data, only the 25% reduction scenarios were retained in the main body of the paper.

C.1.: Targeted and Feasible Production

As shown in Figures 9 and 10, the comparison between the PHL-25% and PHL-50% scenarios (left panel) and the NC-25% and NC-50% scenarios (right panel) shows that the differences in both projected targeted and feasible production are minor. For instance, by 2050, the targeted production under PHL-50% is only 0.46% lower than that of PHL-25%, while feasible production is 0.86% lower. Under 1% is also the difference between NC-25% and NC-50% scenarios. These marginal variations further support the decision to retain the more realistic 25% reduction scenarios in the main analysis.

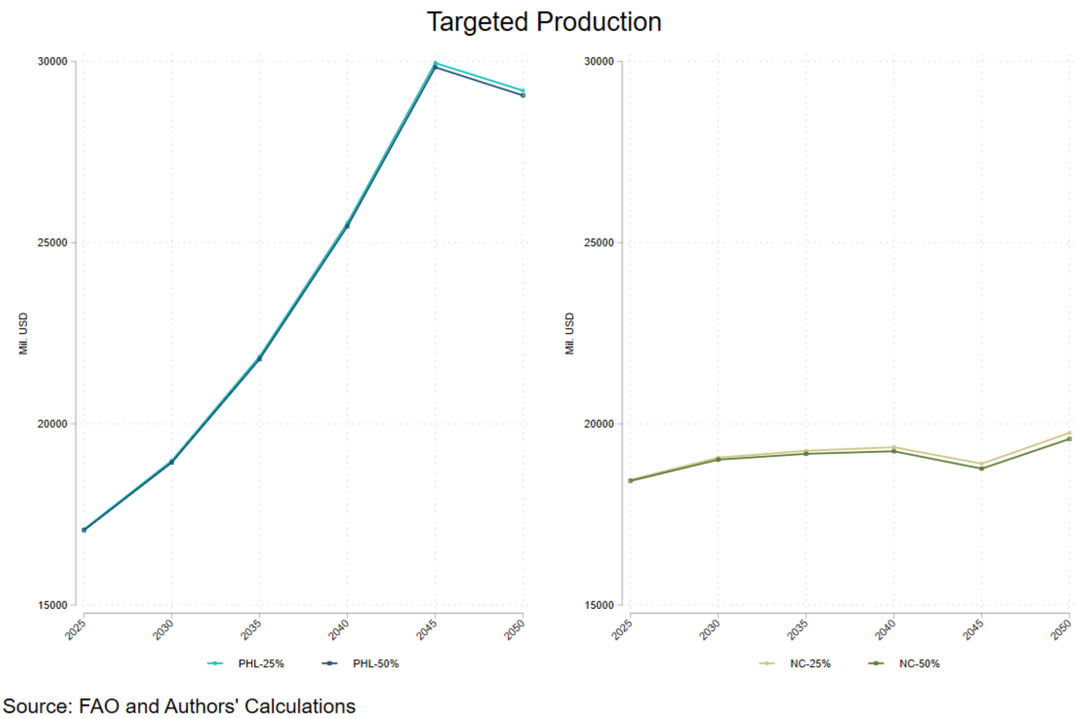

Fig. 9 | Comparison of targeted production under 25% and 50% post-harvest loss (PHL) reduction scenarios. Source: FAO and authors' elaboration using FABLE Calculator (2024). The figure was created using Stata software.

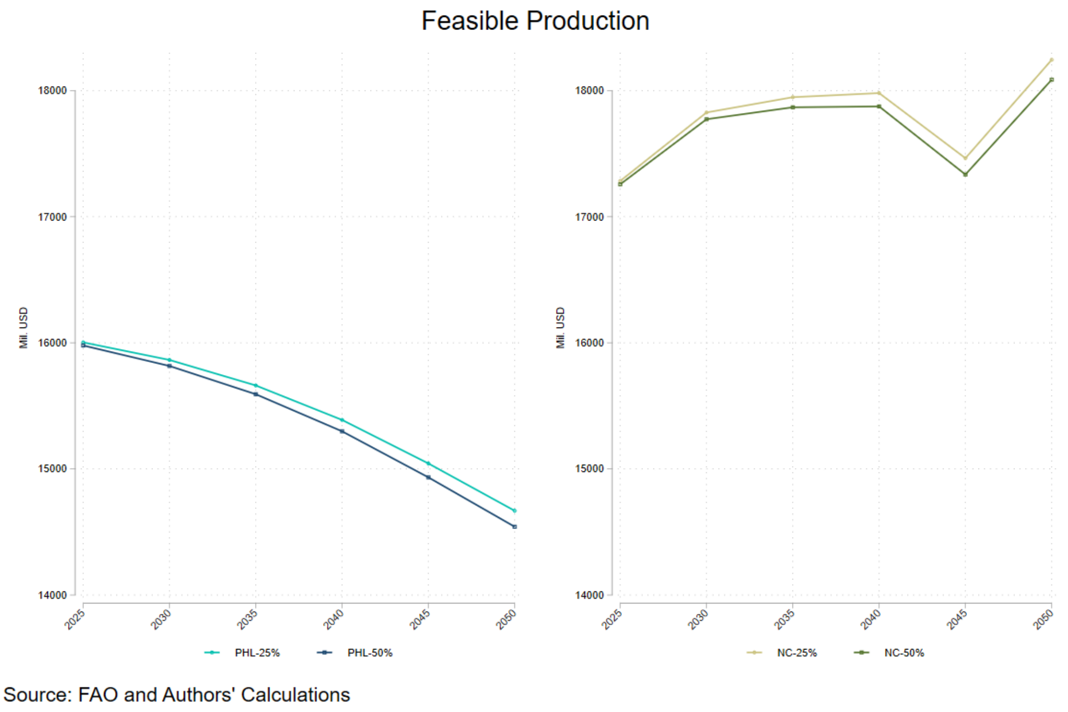

Fig. 10 | Comparison of feasible production under 25% and 50% post-harvest loss (PHL) reduction scenarios. Source: FAO and authors' elaboration using FABLE Calculator (2024). The figure was created using Stata software.

C.2. Production Costs

The comparison of production costs (Fig.11) between the 25% and 50% reduction scenarios in both PHL and NC pathways reveals marginal differences, which become slightly more pronounced over time but remain consistently small. For instance, by 2050, the production cost difference between PHL-25% and PHL-50% is just 0.69%, while the difference between NC-25% and NC-50% reaches 0.75%. These minor variations reaffirm the decision to present only the 25% reduction scenarios in the main analysis, as the higher reduction scenarios show limited additional impact on cost trajectories.

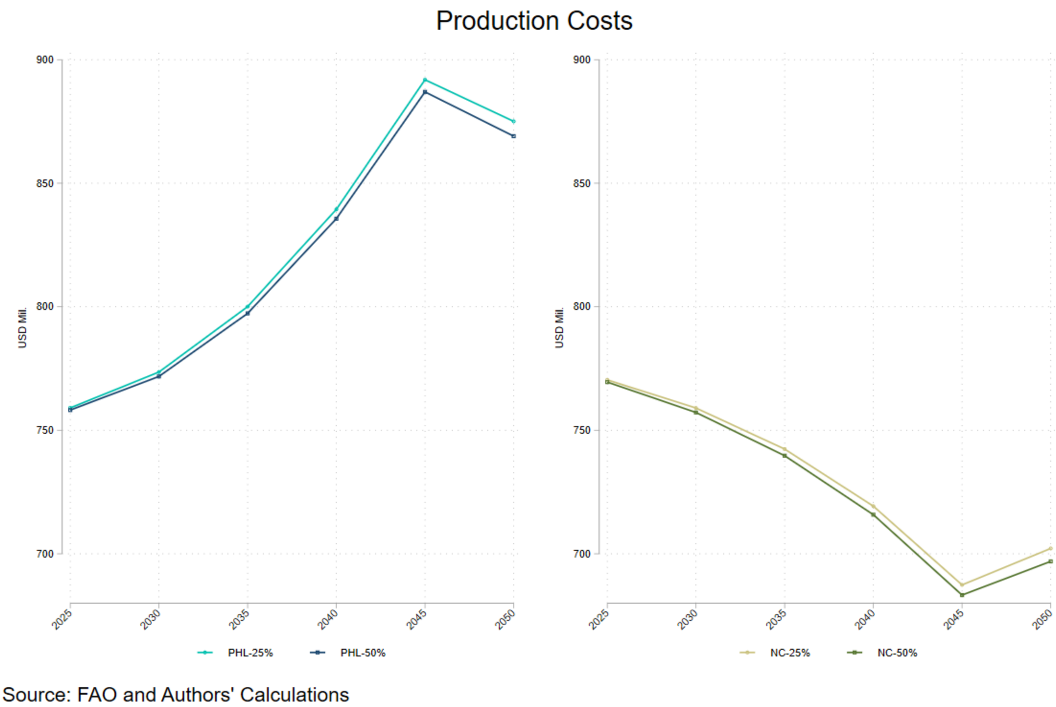

Fig. 11 | Comparison of agricultural production costs under 25% and 50% post-harvest loss (PHL) reduction scenarios. Source: FAO and authors' elaboration using FABLE Calculator (2024). The figure was created using Stata software.

C.3. Total GHG Emissions

The results in terms of GHG emissions show slightly more variation compared to production and cost figures, particularly under the NC scenarios. By 2050, the emissions difference between PHL-25% and PHL-50% is 1.29%, while for NC-25% and NC-50%, the reduction reaches 4.77%. This indicates that implementing more comprehensive policy measures under the NC scenario leads to a somewhat greater decrease in agricultural emissions. However, the overall impact remains modest, and therefore, we continue to support the decision to present only the 25% reduction scenarios in the main results.

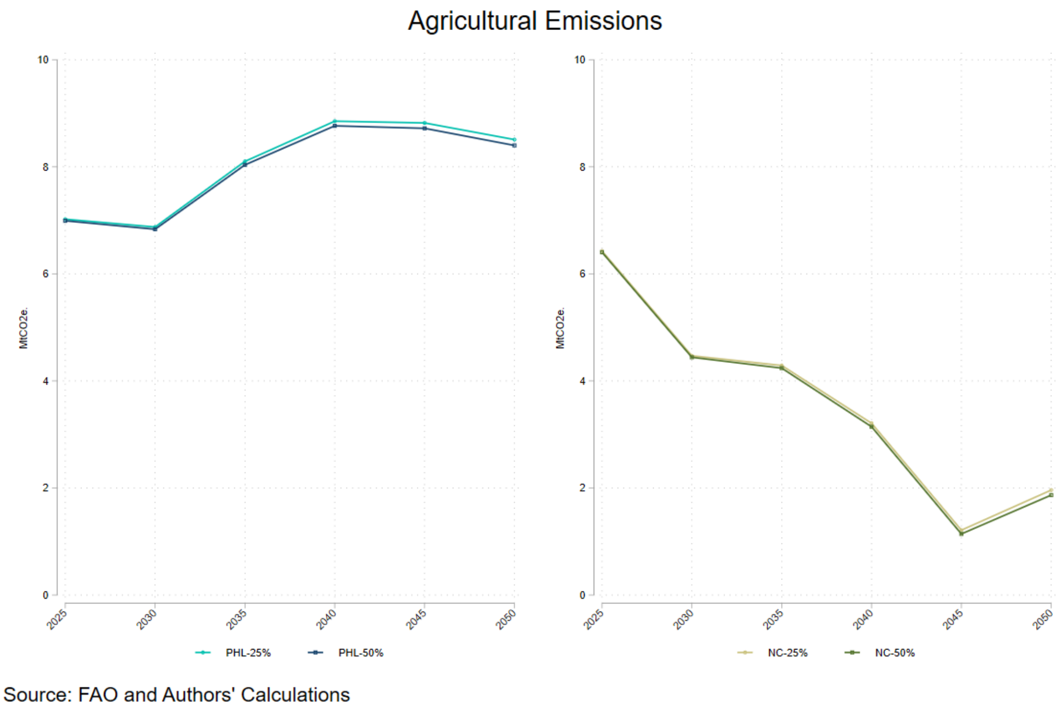

Fig. 12 | Comparison of agricultural greenhouse gas (GHG) emissions under 25% and 50% post-harvest loss (PHL) reduction scenarios. Source: FAO and authors' elaboration using FABLE Calculator (2024). The figure was created using Stata software.