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ORIGINAL ARTICLE

GHG Emission Mitigation of Turkish Agriculture Sector: Potential and Cost Assessment

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Abstract

This study uses a bottom-up optimisation modelling framework to assess GHG (greenhouse gas) emission reduction potential from enteric fermentation, manure management, and agricultural soil-related activities. As a developing European economy, the Turkish agriculture sector has been considered from 2020 until 2050. Four mitigation options are evaluated for their emission reduction potentials: addition of fat supplements to the diet, deployment of centralised biogas facilities, adjustment of fertiliser application rates, and crop rotation with legumes. Results point out the difficulty of emission mitigation in the sector from cost and limited abatement perspectives. Fat supplements have the highest potential (7.2%); others follow, respectively, 4.0%, 0.45%, and 0.35%. Crop rotation has the highest cost and the lowest GHG mitigation potential option considering the opportunity cost. Based on standalone potential assessments, three combined mitigation option sets are implemented. Besides the significant interaction effects, it has been found that the cost-effectiveness of the options depends on electricity and compost revenues.

Keywords Emission mitigation potential and cost assessment · Bottom-up optimisation model

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1 Introduction

Following the adoption of the Paris Agreement to limit the increase in the global average temperature well below 2 °C, signing parties like the European Union (EU) are building long-term low-emission development strategies that outline mitigation, renewable energy, and energy efficiency actions by sectors and measures (European Commission Paris Agreement).

The European agricultural sector significantly contributes to the total GHG inventory, with a share of 11.7% in 2018 (UNFCCC 2019). This number is one of the motivations to emphasise the agriculture sector as a critical area for reaching GHG mitigation targets in the EU. As one of the candidate countries negotiating for accession, climate change policies are becoming increasingly important in Turkey's relationship with the EU. The Paris Agreement was signed in 2016 and ratified by Turkey's parliament in 2021 (Official Gazette 2021). Turkey pledged an emission target to reduce up to 21% of the business-as-usual by 2030 in the Intended Nationally Determined Contribution (INDC) (UNFCCC 2015a). Even though the Turkish government set a net-zero emissions target by 2053, no specific emission reduction target for agriculture in Turkey has been announced.

According to Turkey's National Inventory Report (NIR), the country's emission value calculated for the agriculture sector is 64.9 Mt CO_2e (CO_2 equivalent) for 2018, which corresponds to 12.5% of overall emissions (TurkStat 2020a). Table 1 depicts the GHG emissions from the agriculture sector of Turkey in 2018. This significant share of the sector emissions highlights the fundamental importance of agriculture in the GHG emissions reduction challenge.

GHG emissions in the agriculture sector have been studied extensively within the literature. These studies can be classified into two main groups; studies focused on emissions related to energy use for agricultural activities, while others focused on non-energy activity-related GHG emissions. Regarding energy use-related CO_2 emissions, factors of the emission change are elaborated, such as structural decomposition analysis for China (Yu et al. 2020). It is concluded that the energy structure effect, composition of energy commodities deployed, of China's agriculture plays no effective role in emission reductions. In contrast, the final demand for agricultural commodities is the main driver for the growth of CO_2 emissions. Also, an inclusive multiple model driven by artificial neural networks is deployed for emission projections in Iran for the future (Shabani et al. 2021). Results indicate a nonlinear relationship between economic growth and CO_2 emissions.

Table 1 The sources of GHG emissions in the agriculture sector of Turkey in 2018 (UNFCCC 2021)

Agricultural sub-categories	The rates of GHG emissions
Enteric Fermentation	49.4%
Agricultural Soil (managed soil)	35.0%
Manure Management	13.0%
Others	2.6%
Rice cultivation	
Field burning of agricultural residues (biomass burning)	
Urea Application	
Total	64.9 Mt CO_2e

Regarding agricultural non-energy emission reduction analysis on a global scale, various models are used extensively in the literature. In a multi-model study to assess agriculture's non-CO_2 emission reduction potential, Frank et al. (Frank et al. 2019) concluded that technology options could contribute substantially to GHG mitigation. Besides, demand-side management (dietary changes) would significantly impact emission mitigation efforts to reach the 1.5°C target. For the EU, Fellmann et al. (Fellmann et al. 2018) specifically point out that in complying with a stringent EU-wide agriculture emission target by 2030, production reductions and emission leakage could weigh more than emission reductions achieved by several technological emission mitigation options. Using a system dynamics model, Dace et al. (Dace et al. 2015) assess mitigation options for agricultural GHG emissions in Latvia, concluding that up to 20% reduction could be possible by implementing anaerobic digestion (AD) supported by regulatory policies.

A specific way to assess the potential and costs of different mitigation efforts is within a Marginal Abatement Cost Curve (MACC) framework. In general, MACCs graphically present abatement levels versus costs in an orderly manner to easily determine which options should be prioritised. There are several methodologies to construct a MACC (Vermont and de Cara 2010; Eory et al. 2018), with engineering (bottom-up) MACCs (Moran et al. 2008; Beach et al. 2015; Pellerin et al. 2017) being commonly used in the literature. However, such MACCs are not the right tool to predict the total abatement potentials and relevant cost of combined mitigation options, as the interaction effects between the options may exist and lower the aggregated mitigation potential (MacLeod et al. 2015; Eory et al. 2018; Fellmann et al. 2021). Despite their limitations, bottom-up approaches can highlight the opportunities and low-hanging fruits for mitigation (Eory et al. 2018).

A model-derived approach may assess the combined mitigation options, which can cover the limitations of the bottom-up (engineering) approach (Fellmann et al. 2021). The top-down / model-derived MACC construction approaches deploy optimisation models in which the technological mitigation options are represented explicitly or implicitly depending on the modelling structure. Based on that approach set of variables, constraints, and an objective function organises the interaction towards the desired aim of the system considering the real-life limitations (De Cara et al. 2005). CAPRI (Britz and Witzke 2014), GLOBIOM (Havlík et al. 2014), MAGNET (Woltjer and Kuiper 2014), and IMAGE (Stehfest et al. 2014) are a few examples as the models deployed focusing on agricultural emissions. Besides these models, a few used modeling frameworks include MARKAL (MARket Allocation) (Loulou et al. 2004), TIMES (The Integrated MARKAL-EFOM System) (Chiodi et al. 2016; Loulou et al. 2016; Postic et al. 2017), and MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) (International Institute for Applied Systems Analysis (IIASA) 1995).

Regarding the studies interested in Turkey's GHG emission reduction from the agricultural sector, the number of studies that can be reached is quite limited. Besides, for most of them, the agriculture sector is not the only focus of the studies but a part of the general picture. Non-energy-related studies mostly focus on only a portion of the sector, such as livestock (Ersoy and Ugurlu 2020), while energy-related studies (Dogan 2016; Ozcag et al. 2017) assess the sector from an aggregated perspective using decomposition and statistical models, respectively. Due to the methodologies deployed, they are not evaluating the potential reduction of the emission mitigation options of the country for the near or far future.

Against this background, this paper focuses on the non-CO_2 emissions from enteric fermentation, manure management, and agricultural soil, equivalent to 97% of the agricultural emissions of Turkey. The main aim is to reveal the potential emission reduction and the cost of mitigation options in the agriculture sector. By developing and deploying the TRAGR model, which is based on the bottom-up optimisation TIMES modelling framework, the agricultural network is constructed as a standalone model. The detailed techno-economic content enables the capability to observe the impact of different abatement options on the sector and related emissions. The model results provide a new aspect to decision-makers for non-CO_2 emitting agricultural activities.

A set of GHG mitigation options is adopted upon the reference scenario and analysed. Each mitigation option is implemented individually to assess the emission reduction potentials on a standalone basis. Combined option scenarios are also developed and implemented to evaluate the integrated impact of the options of interest. In conjunction, interactions of the options are investigated for a more realistic emission reduction projection.

2 Agriculture in Turkey

Turkey, as an upper-middle-income country, became self-sufficient in food production and a significant exporter of agricultural products such as wheat flour, nuts, and dried apricots. In 2019, the country's arable land area was 23 million hectares, with 20% irrigated. 67% of the total arable land is used for annual crops, 17% is left fallow, and the remaining 23% is used for vineyards, olive groves, fruit orchards, and vegetable gardens. Cereal is the most important agricultural product group among the annual crops. Wheat, barley, and maise account for 90% of the cereal area sown. In terms of oil crop production, sunflower leads, while soybean and canola follow at a declining rate. Although dry beans, lentils, and chickpeas are traditional crops produced for decades, their shares in the total sown area have decreased significantly over the past ten years, primarily due to the support given to alternative crops and their opportunity cost (TurkStat 2020a).

Animal production shows an increasing trend in response to rising demand. The livestock sector, which consists mainly of cattle, poultry, sheep, and goat, includes extensive and intensive systems. There were 18 million cattle, 48 million sheep, and goats in 2019 (TurkStat 2020a). Modern dairy cattle farms have grown recently due to animal support programs, which are the main reasons for the growth in cattle production. According to the Ministry of Agriculture and Forestry (MoAF), small-size farms in Turkey (with 1-4 head of cattle) are still dominant, representing 60% of 1.38 million registered cattle farms as of 2018. Since these farms are the primary source of enteric fermentation, the growing livestock population increases agricultural emissions.

In this study, historical changes in agricultural products, the current situation, and future expectations in agricultural policies, government interventions, and policies are considered to set up a baseline.

3 Methodology

3.1 IPCC Approach

This study's model structure for estimating GHGs is formed based on IPCC 2006 Guidelines (IPCC 2006). The emission inventory for the agriculture sector includes emissions of methane (CH_4) and nitrous oxide (N_2O) as defined in the common reporting format (CRF) of the UNFCCC. However, the soil carbon dioxide (CO_2) emissions and removals are not accounted for within the agriculture sector, but the 'land use, land use change and forestry' (LULUCF) category. Similarly, CO_2 emissions originating from agricultural activities inheriting fossil fuel use are assigned to the 'energy' category. All other emissions related to agricultural activities, such as the production of synthetic fertilisers, are reported under the category of 'industrial processes' (IPCC 2006).

As mentioned in the previous section, the GHG emissions from enteric fermentation, manure management, and agricultural soil constitute about 97% of all sectoral emissions of Turkey included in the model. For calibration purposes, historical GHG emissions data for the Turkish agricultural sector has been deployed from national GHG inventory submissions (TurkStat 2020b). The GHG emissions originating from the resources mentioned in Table S-1 of the Supplementary Information (SI) have been covered within this modelling effort.

The non-CO2 GHG emissions are calculated using emission factors (EFs) coupled with the amount of nitrogen fertiliser applied or the number of animals of different categories kept on farms. In this study, where the data is available, the Tier 2 approach is followed to calculate GHG emissions (methane emissions related to dairy cows, cattle, and chickens). For detailed information regarding emissions source and Tier approach deployed, please see Table S-2.

3.1.1 The TRAGR Model

Model structure TRAGR is a partial equilibrium, a sectoral, bottom-up model which is a piece-wise linear representation of the Turkish agriculture sector for the non-energy section. The model is based on the TIMES model generator, a bottom-up model generator developed by the "Energy Technology Systems Analysis Program" (ETSAP) of the International Energy Agency (IEA). It represents the structure of single or multiple sectors on a technology-rich basis over a multi-regional, multi-period, and long-term time horizon (Loulou et al. 2016). Paths from the extraction of resources to final use are introduced, and the connections are represented as commodity flows. Technologies include technical (e.g. efficiency, capacity factor, lifetime, emission factor) and economic (e.g. investment, fixed/variable operation& management cost) parameters. Total system cost represents the total cost associated with satisfying the demand commodities such as raw material expenses (e.g. feed), operating cost (e.g. manure management system running cost), investment cost, and revenue generated from sales of commodities produced (e.g. electricity).

TIMES framework uses the linear programming approach to generate a minimum cost system concerning a set of constraints and deploy the best available options. Even though the TIMES model generator has been mentioned as an energy model before, the framework is also convenient for modelling any technology-based bottom-up supply-chain structure. There exist some studies that used MARKAL (the predecessor of TIMES) to model non-energy elements with a bottom-up approach, supply chain of biofuel production with the inclusion of land-use and competition (Sarica and Tyner 2013), and model of biomass use with a land-use competition with a different land-use setup (Gielen et al. 2001). More details can be found in the modelling framework documentation of TIMES (Loulou et al. 2016).

The TRAGR model makes decisions assuming a perfect foresight of future realisations about equipment investments, operating levels, supply, and trades. Therefore, the model outputs consist of levels of these decisions -the system's final structure- their associated costs, the marginal cost of commodities, and process-related and commodity-related emissions.

The model is calibrated for the base year 2015. The long-term modelling horizon covers the period from 2015 to 2050 with five-year time steps. The total system cost is discounted by 5% annually, and the USD of 2015 is used as the currency unit. One hundred twenty-five technologies and related commodities are defined in the model.

In the model, Turkish agriculture has been divided into three groups of activity; livestock, manure management, and crop sector. A basic representation of the flow between these sectors and emission releases is shown in Figure 1. The output of the livestock sector, other than the milk and meat demand satisfied, is processed in a technology mix in the manure management section, and finally, the nitrogen out is the significant input of the crop production. Therefore, the decisions are all connected from the livestock sector to crop production. The model enables price-quantity feedback and commodity interactions between modelled sectors and cooperative behaviour during scenario runs. Details of each subsector are presented in the technology component.

Demand There are eight livestock-related and 15 crop-related exogenous service demands that are given in Table S-3. The demand for 2015 for both sectors has been calibrated to realised values. Demand projections of the milestone years have been based on the critical assumptions of population growth, GDP growth, and demand elasticity of products. The demand for animal products shows an increasing trend between 35% to 82% until 2050.

Since the model does not inherit the land as a factor of crop production, land use assessment has been considered outside of the model structure, coupled with the demand projections. Accordingly, the following assumptions have been carried out; firstly, presuming that the base year total area of selected crops and fallow lands will not change until 2050 (approximately 19.3 million hectares) with the government interventions (food security, agricultural land conservation aims). Then, it is projected that the maximum level of irrigated land is 8.5 million hectares, and it will reach that level by 2040. Lastly, a significant portion of the fallow land is expected to be used favourably for crop production, based on government policies and the potential growth in food demand with the rising population. In detail, the 4.1 million hectares of fallow land in 2015 are expected to be reduced to 2.5 million hectares by 2050, meaning that approximately 1.6 million hectares of arable land would be allocated to crop production until the end of the modelling time horizon.

The ten-year trends in the cultivated area of each selected crop, the maximum and minimum cultivated area of each crop, crop mixture in the base year, and per capita food consumption were considered in demand projections. Additionally, population growth projections (TurkStat 2020c), per capita GDP growth (Republic of Turkey Ministry of Environment and Urbanization 2018), and demand elasticities (Akbay, Cuma, Bilgic,

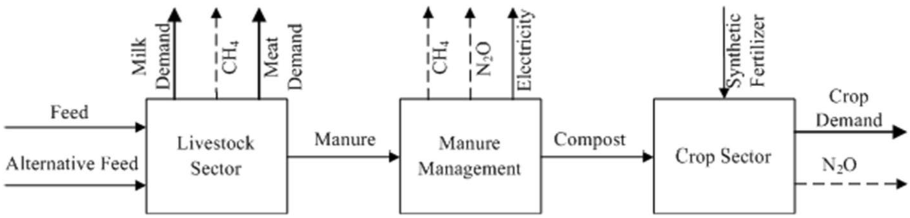


Figure 1 Sectoral breakdown and interactions of the TRAGR

Abdulbaki, Miran 2008) of selected foods were used for demand projections of the crops. Moreover, in the calculations, the base year (2015) crop yield was assumed to be constant throughout the modelling time horizon. In that sense, the possible yield improvement through the change of agricultural practices, as well as the drop in yield levels due to climatic conditions, are not analysed in this framework. In conjunction, the economic impacts of such changes are also out of the scope of this study, such as a decline in the marginal cost of production or competition for land in case of yield losses.

Supply The first supplied commodity group consists of maise silage, wheat straw, alfalfa hay, dairy cattle feed, non-dairy cattle feed, and sugar beet molasses. The feed of livestock technologies has been constructed as a combination of these ingredients with a ratio depending on the cattle breeds: culture, crossbreed, and domestic. Some characteristics, such as weight, distinguish these three cattle breeds from one another. Culture breeds, such as Holstein and Simental, are heavier and more productive than others, while domestic breeds are the smallest and the least productive but more resistant to local weather conditions. The crossbreeds are produced by mating these two. Animal weight is one of the primary parameters that affect animal diet and enteric methane emissions. Additionally, daily gross energy intake values have been used to determine feed rations for each breed. The costs of feed ingredients are listed in Table S-4.

Among domesticated animals, cattle are one of the biggest methane producers when considering the total methane produced by different species. In this context, fatty feeds, as an enteric methane inhibitor, might be thought of as a dietary supplement for the Turkish cattle system. Therefore, an alternative feed ration has been constructed with a fat source (sunflower oil) since adding such an additive to animal diets allows reducing enteric methane emissions from their ruminants (Chilliard and Ferlay 2004). In preparing the new feed ration, sunflower oil consumption at 5% of the dry matter intake (DMI) per day by each breed of cattle is assumed, and the sunflower oil replaced the same mass of untreated concentrate. The details of the base feed and the fat-additive feed alternatives are presented in Table S-5 of SI. The feed of sheep, goats, and poultry are assumed to be standard since there is no abatement strategy for their feeding styles. The other supplied commodity to the model is the nitrogenous (N) fertilisation applied to the soil to cultivate crops and the main factor that causes N_2O emissions. Various N-based fertilisers containing different nitrogen rates were consumed in the base year. The average mineral N content in nitrogenous fertiliser is accepted as 21% since the most common and most used fertilisers in the sector have this ratio as ammonium nitrate and ammonium sulfate. The synthetic fertiliser (including 21% of N), with an average cost of 373 USD/ton, is an alternative to organic fertiliser supplied by the livestock sector of the model and processed in manure management technologies.

Integrating animal manure in crop production systems further reduces synthetic N fertiliser use. Replacing N fertiliser with animal manure is not a 1:1 exchange since they differ in plant N availability. Also, the Phosphate (P)-to-N ratio in manure is higher than the required ratio for crops, and P may, therefore, accumulate in the soil. Since the N content of manures usually is lower than that of synthetic fertilisers, the amount of organic matter to fulfil crop needs is high. The calculated N content ratios for modelled animals' manure are 0.95% for dairy cattle, 0.68% for non-dairy cattle, 2.89% for sheep, 3.43% for goats, and 2.05% for poultry (TurkStat 2020a). In that respect, manure is not a perfect substitute for synthetic fertiliser in numerous aspects. Thus, no more than 25 to 50% manure is permitted to be replacing synthetic fertiliser based on crop type. Land-use is considered implicitly in demand calculations by expert judgments, so not explicitly modelled as a supply component.

Technology Component Technologies, also known as processes, are the main elements of the model to use supplied commodities to satisfy determined service demands. As mentioned earlier, the processes can be grouped into three main activity groups: livestock, manure management, and crop-related processes.

In the livestock sector, ruminant animals (cattle, sheep, goats) produce significant amounts of CH_4 as part of their digestive process. The amount of CH_4 released depends on the type of digestive tract, age, the weight of the animal, and the quality and quantity of the feed consumed. Significant spatial variations in enteric CH_4 emissions exist due to differences in livestock production systems and regional characteristics. An accurate assessment of CH_4 emissions from enteric fermentation requires a detailed description of the livestock population, daily feed intake, and methane conversion rate (Food & Agriculture Organization of the United Nation 2006). Generally, the higher the feed intake, the higher the CH_4 emission. However, the extent of CH_4 production is also affected by the composition of the diet. Feed intake is positively related to animal size, growth rate, and production (e.g., milk, wool, or pregnancy).

Therefore, dairy and non-dairy cattle types (culture, crossbreed and domestic), sheep, and goats are the major ones responsible for GHG emissions from the livestock sector. Enteric fermentation has been included in the model. In addition, poultry has also been included in the model because of its contribution to manure management. All the mentioned livestock animals have been represented as individual processes (see Figure S-1). As shown in Table S-6, cattle breeds have different technical parameters such as life, milk yield, average animal weight, corresponding meat and manure amounts, and capital cost.

The emission factors of each ruminant animal for enteric methane emissions are given in Table S-7. These factors were determined using the formulas given in IPCC 2006 guidelines (IPCC 2006), and parameters CH_4 conversion factor, live animal weight, daily energy intake, and digestibility of animal.

The supply section mentions that each cattle breed has two feed options. Due to the characterisation of cattle's base feed and fat-added feed, variable costs and related methane emissions differ; the other parameters were taken as the same between the same cattle breeds with different diets.

Livestock manure is another source of CH_4 and N_2O, which manure characteristics can regulate, and therefore, emissions can be manipulated via handling, treatment, and storage conditions. In this respect, the manure management sector comprises the manure management systems (MMS) stated in the IPCC 2006 Guidelines (IPCC 2006). Anaerobic lagoon, daily spread, solid storage, composting, anaerobic digesters (AD), pasture, and deep bedding technologies were defined in the model (see Figure S-2). While the AD, composting, and anaerobic lagoon systems require investment and operations and maintenance (O&M) costs shown in Table S-8, other defined systems in the model do not need any cost for management.

Manure is collected separately from each livestock technology in the model to distribute into MMSs with realistic shares. Despite the lack of available national data, to finalise the calibration of the MMS for the base year, data from the General Directorate of Agricultural Research and Policies (Republic of Turkey Ministry of Agriculture andForestry Publications and Data) and the National Inventory Report (UNFCCC 2015b) are reasonably harmonised as in Table 2 and deployed.

Table 2 The base year MMS distribution according to livestock manure types

Manure Management System	Cattle	Sheep	Goat	Poultry
Anaerobic Lagoon	14%			
Daily Spread				14%
Solid Storage	61%			85%
Composting	5%			
Anaerobic digesters	1.5%			1%
Pasture	19%	80%	80%	
Deep Bedding		20%	20%	

Table S-9 in SI shows the CH_4 emission factors from manure management by animal type. These factors were determined according to the parameters such as the methane conversion factor of MMS, animal's gross energy, digestibility of animal, and maximum CH_4 producing capacity of manure using the formulas given in IPCC 2006 guidelines (IPCC 2006).

As mentioned before, N_2O emissions from manure management can occur due to two different processes, direct and indirect. Direct N_2O emissions can be emitted to varying amounts according to animals' selected MMS and nitrogen excretion rates. N_2O emission does not occur if the manure is stored in anaerobic lagoons and ADs or applied to cropland within 24 hours of excretion (daily spread).

Animal manure also contains N in the form of various complex compounds. The conversion of oxidised N to gaseous forms during manure handling, storage, and after field application can represent a significant loss of plant-available N. Both N_2O and, indirectly, NH_3 volatilisation and NO^-_3 leaching contribute significantly to the GHG balance of manure management. Direct and indirect N_2O emission factors by manure management system are listed in Table S-10.

These processes provide worthy economic outputs beyond the emissions released from manure management technologies. First, N content within the manure can be used as fertilisers with the animal-based ratios given before. Secondly, during the anaerobic digestion process, easily degradable organic matter in manure is transformed into biogas (30-40% CO_2 and 60-70% CH_4), which is mainly used to produce heat and electricity with cogeneration plant (or CHP) and the electricity produced can be sold with the price around 6 USD cents/kWh without government subsidy while 13.3 USD cents/kWh for the subsidised projects (Official Gazette 2005). Lastly, based on the manure composition, composting technology generates high-quality compost and low-quality compost by processing the by-product of the AD. These products can be sold for 5 and 15 USD/ton on the market, respectively, if they are not used as a fertiliser by the producer.

In terms of N_2O emissions in agricultural soils that occur through nitrification and denitrification mainly due to fertiliser and manure usage, crop production is a significant contributor. Fifteen crops that constitute nearly all annual cultivated areas in Turkey have been represented as technologies that convert inputs containing nitrogen compounds to related demands and produce corresponding GHG emissions (see Figure S-3).

N_2O is the only GHG emission that is emitted due to soil activities. N_2O emissions due to synthetic N fertiliser, crop residues, animal manure left on pasture and applied to soil have been modelled, atmospheric deposition (volatilisation), and nitrogen leaching/runoff.

GHG emissions from manure left on pastures consist of direct and indirect N_2O emissions from manure nitrogen (N) left on pastures by grazing livestock. In the model, even though pasture is defined as one of the manure management systems, the direct N_2O emissions coming from this system were classified under the agricultural soil.

Each 15 selected crops' N needs and yields associated with them in the model as technical parameters are shown in Table S-11. The relevance between the legumes and other crops creates a window of opportunity for an emission reduction option due to lesser fertiliser use.

4 Emission Mitigation Options and Scenario Formation

4.1 Standalone Mitigation Options

To see the sectoral impact on GHG mitigation, four mitigation options, as listed in Table 3, were determined and modelled under the TRAGR model. These options target GHG mitigation from enteric fermentation, manure management, and managed soils, consisting of 97% of all agricultural sector emissions. The options are modelled and analysed exclusively on a standalone basis.

Methane reduction from enteric fermentation is selected as one of the mitigation options in the sector. Practices for reducing CH_4 emissions from this source fall into three general categories: (i) improved feeding practices, specific agents or dietary additives, (ii) longer-term management changes, and (iii) animal breeding (Smith et al. 2008). One of the feeding practices that result in lower enteric methane levels is fat supplementation. Others include increasing the amount of starch in the diet, using antibiotics such as monensin, and using methane inhibitors such as 3-nitrooxypropanol (NOP) (Beauchemin and McGinn 2006; Romero-Perez et al. 2014; Garcia et al. 2022). All of these methods have a stronger impact on reducing enteric methane. Fat supplementation is recommended in this study due to its high enteric methane reduction rates, low cost, simplicity of implementation among farmers, and expert opinions from Turkey's Ministry of Agriculture and Forestry. This method increases some of the commonly used feed ingredients in the diet. A traditional ruminant diet, depending on whether the animal is primarily grazing or fed a high proportion of concentrates (non-forage feeds high in energy and protein content, e.g., a mixture of grains, soybean meal, sugar beet pulp) contains 1.5-3 dry matter % (DM%) fat. Increasing the fat content reduces enteric CH_4 emissions from the rumen via biological processes in the digestive system. The CH_4 reduction is proportional to the fat content, but due to potential health issues and practical aspects, a maximum limit of 5-6 DM% total fat content is acceptable (MacLeod et al. 2015). It is determined that each 1% of fat added to the diet will result in a 5% reduction of enteric CH_4 emissions (MacLeod et al. 2015). As a

Table 3 Selected mitigation options

Name	Selected Mitigation Options	Targeted GHGs
MO1	Addition of fat supplements to the diet	CH_4
MO2	Deployment of centralised ADs (biogas facilities)	CH_4, N_2O
MO3	Adjustment of fertiliser application rates	N_2O
MO4	Crop rotation with legumes	N_2O

fat supplement, sunflower is selected by considering Turkey's economic and supply advantages and applying them within the farms. The expected maximum coverage is to reach 30% of the overall feed consumption annually by 2050. The change in the animal diets with the additive fat supplement is shown in Table S-3.

AD is another mitigation option to mitigate GHG emissions from manure management. It is selected and modelled to reduce CH_4 and N_2O emissions from livestock by improving animal manure handling and storage conditions. AD is a natural process driven by microorganisms producing biogas and upgrading to biomethane. As a by-product, digestate (organic fertiliser) is produced, a nutrient and organic matter-rich product that can be used as fertiliser on the soil. The biogas can be burned directly in a gas turbine, combined heat and power system (CHP), or combined cycle gas turbine (CCGT) to produce electricity. The technical and economic parameters of electricity production technologies are shown in Table S-12 of SI.

It is assumed that centralised biogas plants to be built would collect manure from big-scale animal farms that own at least 150 cattle or from several close-located cattle farms that own at least 150 cattle in total. When considering Turkey's current farming system's scale and geographic distribution, the highest penetration level of the technology that can be attained is limited to 25% of all cattle and chicken manure processes by 2050.

For the third option, fifteen crops were selected to evaluate their N-fertilization application and compare them to the required amounts. The nitrogen fertiliser needs of crops were determined using the related guideline (Republic of Turkey Ministry of Agriculture and Forestry 2006). According to the calculations based on the data received from the MoAF, it is determined that nitrogen fertiliser is applied to seven out of fifteen crops in excess of their needs, which can lead to adverse environmental impacts such as N_2O emissions into the atmosphere. This option aims to gradually decrease the fertiliser rates to the required levels until 2050 while keeping the same yield levels for maise, dry bean, sugar beet, canola, alfalfa, cotton, and soybean. However, keeping the same yield levels requires extra efforts adding a financial burden on the producers. As well as the cultural attitude towards excessive use, it is not easy to overcome. In that regard, required training and communications with the farmers need time and financial support to remove the barriers for reaching the targets. Even though these costs have been assessed based on collected data, they are not implemented since the costs associated with overcoming cultural barriers have not been covered in other options considered in this study.

As the final mitigation option, crop rotation with legumes is selected to reduce N_2O emissions from the soil. Thus, the N fertiliser needs of the preceded crop will be reduced (Liu et al. 2016). According to crop mix projections calculated using the data provided by TurkStat and MoAF, a well-suited crop rotation plan for Turkish agriculture is prepared for both rainfed and irrigated agricultural systems, as shown in Table 4. The N requirements of the crops rotated are shown in Table S-9 of SI.

Table 4 Crops to be rotated with legumes

Crops to be rotated	Legumes
Wheat (irrigated)	Chickpea (irrigated)
Wheat (rainfed)	Chickpea and vetch (rainfed)
Barley (irrigated)	Lentil (irrigated)
Barley (rainfed)	Lentil and sainfoin (rainfed)
Maise (irrigated)	Soybean and vetch (irrigated)

4.1.1 Combined Mitigation Options

Even though the standalone mitigation options give insight related to possible potentials that can be obtained, assuming that total abatement potential can be reached by summing them up is misleading. In order to reach higher levels of abatement levels in line with the 1.5°C climate change target, it is inevitable to combine the mitigation options in which the interaction between the options may lead to lower total mitigation than the sum of each standalone option.

In this study, three sets of scenarios with a combination of standalone mitigation options have been designed. Starting by combining the two lowest potential mitigation options, the first combined mitigation option set (CMO1) is designed to reflect the total abatement potential of these two. Combined mitigation option set 2 (CMO2) is constructed on top of CMO1 by adding MO2, AD. Likewise, the combination of MO1 and CMO2 has formed the combined mitigation option set 3 (CMO3). Table 5 summarises the options considered within each combined set.

5 Results

5.1 Reference Scenario

The reference scenario is designed to track GHGs trends with the current policy trend in the agriculture sector until 2050. As presented in Figure 2, sectoral emissions will increase by 88% from a level of 54 Mt CO_2e in 2015 to 101 Mt CO_2e in 2050. The overall emission increase results from agricultural production increases. Since no yield change is studied for crop production structure, it can be concluded that emission increase has a linear relationship with overall crop production quantities. However, the change in the demand structure disturbs this relation during the modelling time horizon, as can be seen in sugar beet demand resulting in less synthetic fertiliser use than expected. On the other hand, livestock emissions exhibit a dynamic pattern due to the interaction between manure management systems and the livestock production mix. While similar impacts also hold for the cost of production, expected total cost of sectoral activities are expected to increase from 25 billion USD in 2020 to reach 32 billion USD for the sector in 2050.

The sectoral breakdown of the emissions can be seen in Table 6 throughout the modelling horizon, related to enteric fermentation, manure management, and agricultural soil. In that regard, enteric CH_4 emissions will increase by 117% from a level of 1.06 Mt CH_4 in 2015 to 2.31 Mt CH_4 in 2050. The main driver of this trend is the increase in the number of livestock. However, the increase in enteric fermentation related CH_4

Table 5 Coverage of the designed scenarios

Option	Combined Mitigation Options Set 1	Combined Mitigation Options Set 2	Combined Mitigation Options Set 3
MO1	×	×	√
MO2	×	√	√
MO3	√	√	√
MO4	√	√	√

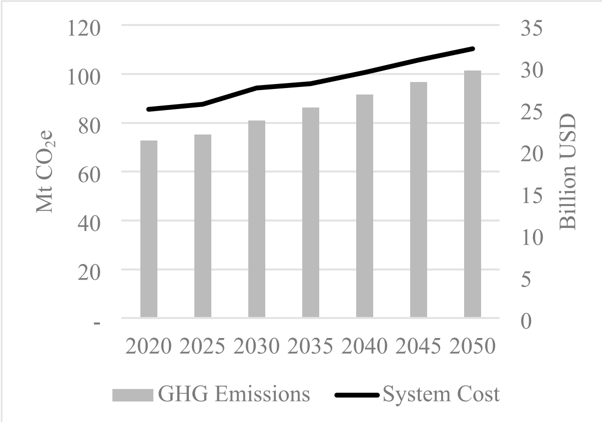


Figure 2 Expected GHG emission (left axis) and the total cost of sectoral activities (right axis) of the reference scenario

Table 6 Agriculture sector GHG emissions (Mt CO_2e) breakdown in the reference scenario

	2015	2020	2025	2030	2035	2040	2045	2050
Enteric Fermentation (CH_4)	26.6	36.9	41.6	45.2	48.5	51.8	54.8	57.8
Manure Management	8.2	9.8	10.7	11.5	12.2	12.9	13.7	14.3
CH_4 from manure management	3.8	4.1	4.2	4.3	4.4	4.5	4.6	4.7
Direct N_2O from manure management	2.8	3.7	4.2	4.7	5.1	5.5	6.0	6.4
Indirect N_2O from manure management	1.6	2.0	2.3	2.5	2.7	2.9	3.1	3.3
Agricultural Soil	18.9	25.9	22.8	24.2	25.6	26.9	28.1	29.3
Synthetic N fertiliser application (N_2O)	7.6	11.3	7.4	7.5	7.8	8.0	8.2	8.4
Manure left on pasture (N_2O)	2.7	3.7	4.2	4.6	4.9	5.3	5.6	5.9
Organic fertiliser (manure applied to soil) (N_2O)	2.4	3.2	3.6	4.0	4.4	4.7	5.1	5.4
Crop residues (N_2O)	3.8	4.2	4.4	4.6	4.7	4.9	5.0	5.1
Indirect N_2O emissions through atmospheric deposition and leaching/runoff	2.5	3.4	3.3	3.5	3.7	4.0	4.2	4.4
Total (CO2e)	53.8	72.7	75.1	80.9	86.3	91.6	96.7	101.4

emissions is less than the increase in the number of livestock, a 140% increase by 2050 compared to 2015. The change in the demand structure, favouring sheep and goat meat, changes the enteric fermentation emission mix as well as the level of enteric fermentation emissions.

The MMS distribution exhibits very steady dynamics during the modelling horizon. Under no government intervention, solid storage is expected to be the dominant manure management technology; its share is initiating from 48% in 2015 and reaching up to 55% in 2050 in a monotonically increasing trend. Within the modelling horizon, pasture, deep bedding, anaerobic digestion, and daily spread exhibit nearly constant shares of 27%, 8%, 1% and 1%, respectively. Besides, the anaerobic lagoon drops its share from 11% to 5%, while composting decreases from 4% to 2% between 2015 and 2050. GHG emissions from manure management increased by 73% from 8.2 Mt CO_2e in 2015 to 14.3 Mt CO_2e in 2050. Most GHG emissions from manure management within the modelling horizon belong to N_2O emissions (direct and indirect) and stabilise around 68%.

Results show that GHG emissions from agricultural soil will increase by 55% from 18.9 Mt CO_2e in 2015 to 29.3 Mt CO_2e in 2050. The agricultural soil GHG emissions composition is dominated mainly by synthetic N fertiliser. Emissions routing from the synthetic N fertiliser diminishes to 29% by 2050, starting from 40% in 2015, while organic fertiliser application, manure left on pasture, and indirect N_2O (deposition and leaching) emissions fill the gap. In relation to the increasing number of livestock, MMSs output, organic fertiliser, increases rapidly as well and leads to an increase in agricultural soil emissions faster than the synthetic counterpart. This shows the importance of the manure management system technologies, exhibiting an insight to the reader in which the AD deployment in the reference scenario is limited.

5.1.1 Standalone Assessment

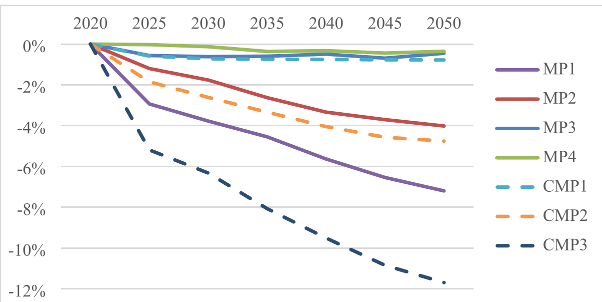
The TRAGR model results show that MO1 has the highest GHG emission reduction potential of 7.2% until 2050 compared to the reference scenario. As displayed in Figure 3, the second-highest mitigation potential belongs to MO2 at 4.1%. MO3 and MO4 show only a limited GHG mitigation potential with 0.45% and 0.35% with respect to reference scenario.

Within the mitigation options, the MO3 is expected to have no additional application cost compared to the reference scenario, while it also exhibits negative abatement cost (-41 USD per ton CO_2e avoided). Despite the win-win situation of the option, cost reduction while reducing the emissions, the unsung cost component is related to training as well as communications with the farm owners to overcome social and cultural barriers.

The MO1 is the next cost-effective option that exhibits an additional cost of 1.5 billion USD in 2050. The cost-intensive nature of the option limits the penetration within the livestock industry to 30%. The TRAGR results reveal that the average cost of mitigation will be around 200 USD/ton CO_2e, which exhibits the costly structure of the option. The easiness of the implementation of fat supplements to the diet of animals is curtailed by their high costs. For example, logistics problems due to the excess of small-scale cattle farms and difficulties in the supply of sunflower oil boost the cost significantly for emission strategy deploying fat supplements.

The integration of ADs to the farms, as in the MO2, is the following effective option, with an extra annualised system cost of 1.5 billion USD in 2050. One of the challenges that create this outcome is the small farm scale. Only 25% of the cattle and chicken farms are suitable for such integration, limiting the applicability and economies of scale for decreasing the marginal cost of implementation. MO2 distorts the MMS and mostly favours AD by lowering the shares of solid storage and anaerobic lagoons. The capital-intensive nature

Figure 3 GHG mitigation potentials of options compared to the reference scenario



of the equipment needed to be installed is another barrier that creates huge annualised costs, as shown in Tables S-6 and S-10 of the SI.

MO4, crop rotation, counterintuitively has been found to be the most expensive mitigation option with an expected annualised additional cost of 2 billion USD in 2050. Within the crop rotation process, the non-legume crops that have been avoided for that period create a significant opportunity cost for the farmer. Without government financial support, the implementation is unrealistic, and the average cost of mitigation is off the charts. Another reason for the high cost is that income loss occurs when the legumes are produced, which have lower yield levels and prices in place of the higher price crops like wheat, barley, and maise (CME Group NYMEX). This outcome is also due to the limited legume plantation area, which creates an unbalanced market structure for legumes and other crops. The size of the cultivation areas of legumes is much smaller than that of wheat, barley, and maise. The total cultivation area of wheat is around 22 times bigger than chickpeas and around 18 times bigger than cow vetches. Similarly, the total cultivation area of barley is around 12 times bigger than a lentil and around 14.5 times bigger than sainfoin. The vast differences between the size of cultivation areas of crops being rotated contribute to the increase of the cost per ton avoided.

5.1.2 Combined Assessment

Combined results reveal more interesting outcomes for the decision-makers. As displayed in Figure 3, no significant emission reduction can be obtained by combining the adjustment of fertiliser application rates and crop rotation with legumes in CMO1. Besides this observation, it is also clear that two options overlap and result in 24 kton of CO_2e abatement loss, lowering the total abatement potential down to 790 kton CO_2e (0.78%) in 2050, as shown in Figure 5c. Based on detailed analysis, adjustment of the fertiliser rate simultaneously with the crop rotation for the crop switching areas (maise vs soybean) is not meaningful since the crop rotation option already assumes realistic fertiliser rates according to the yield expectations in TRAGR. However, the model chooses not the implement the crop rotation option but the adjustment of the fertiliser rate in order to avoid the opportunity cost of the crop rotation, which leads to the reported abatement loss.

With the addition of AD to CMO1, the CMO2 points out a 4.8% reduction compared to the reference scenario in 2050. Compared to the sum of standalone options abatements inherent in CMO2, a 1.3% loss occurs in the combined case. Distortions in the manure management system the combination of AD and CMO1 creates a slightly different MMS structure compared to MO2, resulting in a slightly higher manure-related CH_4 and direct/indirect N_2O creating a negative interaction effect.

Combining the highest mitigation option, MO1, with CMO2 mimics the negative interaction effect of previous combined option sets. CMO3 offers an 11.7% emission reduction potential in 2050. Even though the sum of the standalone options' emission reduction potentials points out a higher mitigation level, a loss of 2.7% from this expectation is observed, resulting in overall reduced combined performance. This outcome is mainly due to the need for a reduction in the total production cost. Primarily, the cattle type is shifted from domestic beef cattle fed with fat supplement to culture dairy cattle fed with fat supplement. This action diminishes the emission reduction potential of the option and emits relatively higher enteric CH_4. However, this change creates an opportunity window for the MMS cost reduction by increasing the daily spread and deep

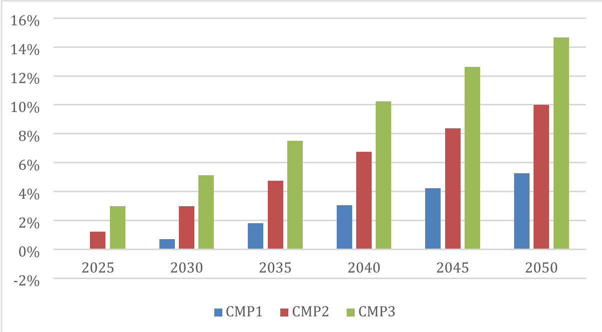


Figure 4 The additional cost of combined option sets with respect to the reference scenario

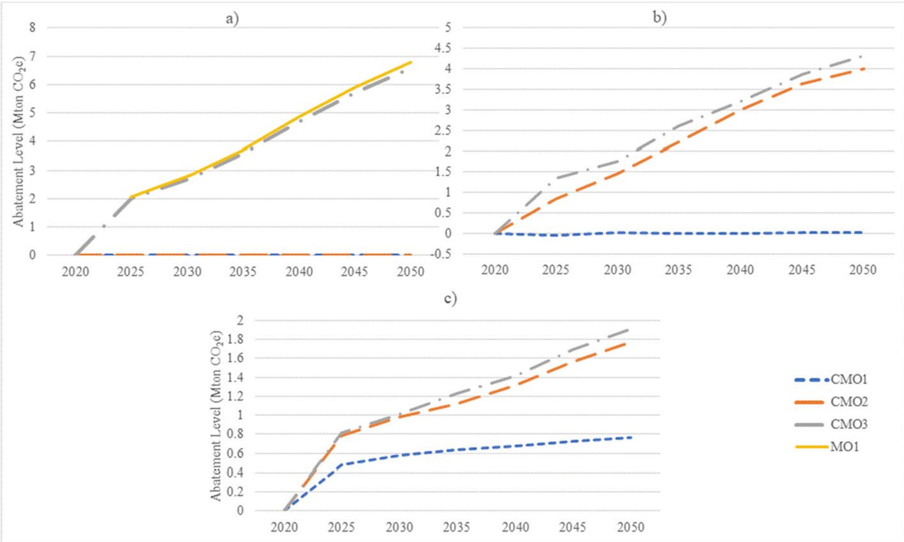


Figure 5 Abatement dynamics of a) enteric fermentation b) manure management c) agricultural soil

bedding shares while decreasing the solid storage and anaerobic lagoon dominancy. This set up also creates a negative interaction effect on the MMS-related emissions.

With CMO2 and CMO3, 4.8% and 11.7% of emission reduction compared to the reference scenario are reachable. Model outputs indicate that no easy emission reduction is possible within the agricultural sector. The sector needs to overcome an additional 10% and 14.7% annualised system costs in 2050 to serve the same population, as shown in Figure 4. These total system cost increases indicate price increases for all food products within the market. The results suggest that government support may be crucial to reach the targeted ambition levels based on these cost disturbances.

As shown in Figure 5a, the only contributor to the abatement in enteric fermentation emissions is the addition of fat supplements into cattle diets. As mentioned earlier, 6.6 Mton of annual abatement seems to be in reach by 2050; however, the interaction effect rasps the gain of the option when used in a combined manner with other options in CMO3.

The effectiveness of the scenarios in reducing GHGs mainly depends on the level of electricity generation from AD. Under the reference case, around 0.8 TWh of electricity per year is generated and benefits from YEKDEM subsidies within 2030. However, electricity generation reaches 16.32 TWh in CMO2 and CMO3 cases in 2050. The electricity output level is not affected by the other options. Electricity production also lowers the manure volumes to be managed, which directly reduces the load of the MMSs, thus lowering the related emissions, which can be seen in Figure 5b. Besides, AD contributes significantly to soil emission reduction, as shown in Figure 5c, due to the reduced manure reaching soil-based MMSs. However, the exact contribution of the AD is dependent on the existence of other options; interaction effects generally diminish the savings. Despite the governmental support, limitations regarding lack of technical infrastructure, unfavourable geographical and climatic conditions in some production regions, being more feasible of manure collection from cattle and chicken farms for biogas production rather than other animals, and the redundancy of small-scale farms creates economic limitations within the market as well as higher cost of implementation than expected.

6 Discussion & Conclusions

This study aims to assess Turkey's agricultural sector regarding possible GHG mitigation policies considering society's social, economic, and geographic limitations. The Turkish agricultural ecosystem has been studied and modelled in this context through a techno-economic bottom-up optimisation approach. The findings of this study provide information on how Turkey's agricultural sector could contribute to achieving the country's 2053 GHG mitigation targets. The assessment of emission mitigation potentials of specific options on both a standalone as well as a combined basis helps to reveal more realistic emission reduction potentials.

Four emission mitigation options have been selected targeting livestock (addition of fat supplements to the diet), manure management (deployment of centralised biogas facilities), and agricultural soils (adjustment of fertiliser application and crop rotation with legumes). Even though other mitigation options deem to exist in the agricultural abatement context, these four are prominent due to their applicability without disturbing the current business cycle.

The negative cost of the mitigation option indicates that farmers would benefit by adjusting fertiliser rates. However, despite the attractiveness of this option, the producers seem to have no willingness for its application, as also pointed out in the literature (Moran et al. 2013; Pellerin et al. 2017). Regarding crop rotation with legumes, the literature reports the cost of mitigation per ton CO_2e avoided in the range of 20-50 €/ton (MacLeod et al. 2015; Pellerin et al. 2017). However, this option shows higher costs and low abatement potential in our study. This discrepancy between the literature and this study is because of the revenue loss due to product switching, which is accounted for, unlike in other studies.

The most favourable mitigation option is fat supplements that reduce methane emissions due to enteric fermentation. The potential abatement level is the highest, with 7.2% mitigation compared to the reference case by 2050. This favourable potential level is accompanied by the cost of mitigation in the order of 200 USD/ton CO_2e. Similar (Pellerin et al. 2017) or higher (Fellmann et al. 2021) abatement cost related to oily seed substitution in the animal diet reported by other studies. This comparison reveals the risk of higher mitigation costs based on the assumptions in relation to the oily seed chosen (sunflower, linseed etc.) or the price of these commodities. Anaerobic digestion as an alternative MMS is a multi-benefit mitigation option, reducing soil and manure management emissions. The option also creates an emission abatement for the electricity sector. However, this reduction is reported not in agriculture but in the electricity generation sector, which moves the abatement out of the scope of this analysis. The cost per ton of CO_2e avoided for this study is much higher than the reported levels in other studies (MacLeod et al. 2015; Pellerin et al. 2017; Fellmann et al. 2021), which ranges from 55 to 150 €/CO_2e. The main reason for this difference is the electricity price differences; the average electricity price in the EU is three times higher than in Turkey for the first half of 2022 (Eurostat 2022).

The interaction of the mitigation options points out a different dimension that needs to be considered in the phase of implementation of multiple options at the same time for long-term mitigation efforts. Individual analysis of the options reveals the standalone GHG mitigation potentials. However, for this study, the combined abatement levels fall behind the expected numbers when the options are implemented synchronously. The interaction of the options creates diminishing returns when implemented on top of each other. For the full combination of the options in this study, the interaction results in a 3.6% potential loss in the CMO3. For every additional option , a similar analysis should be carried out for future studies; one should never forget that the outcome does not need to be negative, but positive interactions may occur in each case, depending on if the alternative practices have competing or complementary relations (MacLeod et al. 2015; Eory et al. 2018).

In the international context, feed changes and biogas digester options have also been studied in the context of livestock and manure management (Höglund-Isaksson et al. 2020). According to their results, the potential mitigation would be around 11% for enteric fermentation and manure management emissions in 2050 maximum technically feasible reduction. In our study, due to the penetration limits imposed, the sum of potential emission mitigation of these two options is found to be around 11.2%. However, their cost figures are around 20 €/tonne CO_2-e to 600€/tonne CO_2-e. Numbers found in this study are around the mid-level of this scale. This difference is mainly due to the limited penetration levels imposed; thus, higher penetration levels would increase potential abatement levels as well as costs.

Even though it is not possible to make a one-to-one comparison, Chiodi et al.(Chiodi et al. 2016) point out 6% and 16% emission reduction for the agriculture sector compared to 1990 levels by 2050 for 341 and 683 €/ton CO_2e, respectively. This cost range indicates a similar cost pattern related to our CMO2 and CMO3 cases abatement costs of 668 and 398 USD/ ton CO_2e corresponding to 5% and 12% reduction levels compared to the reference scenario levels. Their work has also concluded that fat supplements are found to be the highest abatement potential option contributing to the emission mitigation effort. Besides, AD is also one of the significant contributors in that sense.

Besides these, studies that have been conducted in Southeast Asia (Hasegawa and Matsuoka 2012, 2015; Hoa et al. 2014; Jilani et al. 2015) reported lower mitigation costs for higher abatement levels. However, base year differences in terms of production environment (e.g., roughage use as feed is insignificant in Turkey's livestock sector) may explain the cost differences compared to the Southeast region.

Rice cultivation is not covered in this study due to the limited cultivation area. Nevertheless, it is a critical CH_4 emission source globally and may become an important concern for Turkey if the cultivation area increases over time. In that regard, methane reduction techniques like midseason drainage (Yan et al. 2005), intermittent irrigation and other methodologies (Yao et al. 2017; Islam et al. 2022) should be considered and planned to be deployed over time as an emission reduction pathway.

In line with other studies, our analysis confirms that standalone mitigation options provide insight into mitigation potentials and can reveal low-hanging fruits for mitigation. However, it also shows the importance of analysing the options in a combined framework to set up a more realistic expectation of mitigation potentials (MacLeod et al. 2015; Eory et al. 2018; Fellmann et al. 2021).

Implementation of the mitigation options considered is not assumed to be voluntary, and the details of the producer/consumer support mechanism are not covered within the scope of this study. Besides, the costs of the options used within the body of the model include only the engineering and/or opportunity costs if they exist. The cost of implementation is not included for required training, public communications to stimulate the deployment of mitigation options, etc. Therefore, resultant model costs have been only an underestimation of real-life applications.

In future works, the standalone agriculture model can be integrated into an economy-wide national model for a more comprehensive analysis regarding GHGs mitigation efforts. Land and water nexus are out of the scope of this study because of the lack of data. Therefore, the effect of water on crop yield is not considered. Also, for land usage, disaggregation of zones and determination of the products and their needs would be a massive contribution but requires much effort.

Regarding policy recommendations, our analysis shows that the mitigation options come along with significant cost increases within the agricultural sector of Turkey. In this respect, support mechanisms for the producers seem crucial to minimise the impact on producers and consumers. Turkey can set up emission trading and/or carbon pricing mechanisms to raise funds to promote emission mitigation options within the agricultural sector coupled with the necessary regulatory framework to make the funding flow to the right places.

As a final note, this analysis reveals that regulation of fertiliser use should be implemented in the early starter phase of the short and medium-term emission mitigation efforts due to its ease of implementation and benefits inherited in the production cost improvement. Fat supplement option should follow in the later stage to initiate high abatement gains while in the short term, necessary infrastructure and regulatory framework must be prepared to follow. The more costly digester option should be incentivised for large-scale farms for all livestock to reach the maximum abatement potential. Crop rotation is found to be not an effective as well as highly costly option to suggest as an option for future mitigation efforts.

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Data Availability Most of the public data analysed during this study are included in this published article. Its supplementary information files and the source links are shared as much as possible for convenience. Public data that does not have a direct link and/or that is not publicly available is available from the corresponding author upon reasonable request and with the permission of relevant institutions.

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