



Evaluation of Greenhouse Gas Emissions of Quinoa Seed Production in Greece

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RESEARCH ARTICLE

Abstract

Population growth has led to an increase in food production, resulting in an increase in agricultural products in terms of quantity and quality. Quinoa (*Chenopodium quinoa* Willd.) cultivation is prevalent in most areas of the world due to its high-quality grain and its potential to produce high yields under tough growing conditions. This study aimed to investigate all greenhouse gas (GHG) emissions generated by quinoa seed production in Greece and their relationship with farm-related factors, from fertilizer production to energy consumption for all cultivation techniques. The amount of all GHG emissions was estimated using Cool Farm Tool software. In order to collect data, a questionnaire including questions regarding cultivation details, soil characteristics, inputs, fuel, and water use was distributed and completed by forty quinoa producers from Central Greece. Accordingly, the estimated carbon footprint values per hectare and per kilogram of quinoa seed were 1,159.65 and 0.48 kg CO₂-eq, respectively. The present research also found that the highest CO₂-eq emissions per kilogram of quinoa seed were found to be associated with the production of fertilizers, with a value of 0.20 kg CO₂-eq corresponding to 40.88% of the total emissions per kilogram of produced seed. Consequently, attention must be given for the mitigation of the environmental impact of quinoa seed production. It is particularly important to manage chemical fertilizers and agricultural machinery properly in order to ensure the sustainable cultivation of quinoa.

Keywords: carbon dioxide emissions; climate mitigation; sustainability; quinoa cultivation

INTRODUCTION

Population growth has led to an increase in food production, resulting in an increase in agricultural products in terms of quantity and quality. Food security is increasingly taking into account factors such as greenhouse gas emissions (GHGs), as well as concerns about the population growth impact on climate change (Lotfalian Dehkordi and Forootan, 2020; Pereira et al., 2021). A major challenge facing agriculture is improving food yields without increasing greenhouse gas emissions. European Union (EU) has designed several strategies (the Common Agricultural Policy, the European Green Deal, Farm to Fork, and One Health) to tackle climate crisis and to reduce GHGs emissions. In July 2021, the European Commission adopted, a package of legislative proposals entitled "Fit for 55" that is part of the European Green Deal, which is intended to strengthen the EU's position as a global leader in climate change. Among the goals of the package are to modernize current legislation in line with the EU's 2030 climate target and to introduce new policy measures in order to facilitate the transformations needed in society, industry, and the economy to achieve climate neutrality by 2050 and to

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support climate neutrality by 2030 by reducing net emissions by at least 55% (compared to 1990) (European Council, 2023). For the agriculture sector, the Land Use Change and Forestry (LULUCF) Regulation sets a binding obligation on the EU to reduce emissions and increase removals (European Commission, 2023). As a result of the “Fit for 55” package, the provisions have been made more ambitious. Among the new rules, an increased EU-wide target of 310 million tonnes of CO₂ equivalent is set by 2030. Each Member State is required to set binding national targets. A general approach was set by the Environment Council on 29 June 2022 regarding the revised LULUCF Regulation. In November 2022, a provisional agreement was reached with the European Parliament, and the Regulation was adopted by the Council in March 2023 (European Council, 2023).

Agricultural practices such as fertilization and irrigation contribute to the increase in greenhouse gas emissions from the soil into the atmosphere, which in turn affects the biogeochemical process of carbon and nitrogen in the soil. There are estimates that greenhouse gas emissions from arable land contribute up to 13.5% of anthropogenic emissions worldwide (IPCC, 2007), with carbon dioxide, methane and nitrous oxide being the most significant (Paustian et al., 2004). The majority of carbon dioxide (CO₂) emissions are associated with microbial decomposition or with the incineration of plant residues and soil organic matter. The production of methane (CH₄) occurs as a result of the breakdown of organic matter under anaerobic conditions, which is mainly caused by the digestion of animals, manure, and flooded rice crops (Mosier et al., 1998). In soil or in manure, nitrogen (N) is converted into nitrous oxide (N₂O), which becomes more intense when the amount of N available to plants exceeds the amount needed for their growth, especially in wet conditions (Oenema et al., 2005). Agriculture accounts for 52% and 79.3% of total methane (CH₄) and nitrous oxide (N₂O) emissions, respectively. Increased concentrations of greenhouse gases (GHGs) and rising temperatures as result of GHGs are expected to have a variety of direct and indirect impacts on crop production, including changes in water availability (rainfall and relative humidity) as well as increased pest and disease incidence (FAO, 2015). Reduced greenhouse gas emissions from agricultural practices while maintaining yields is an essential and critical task for all crops. Improving farming practices is an advocated strategy for lowering greenhouse gas emissions from cultivated areas. However, because farming practices differ from crop to crop, this strategy is largely dependent on farming techniques (Malhi et al., 2021).

Quinoa (*Chenopodium quinoa* Willd.) cultivation is prevalent in most areas of the world due to its high-quality grain and its potential to produce high yields under tough growing conditions (Angeli et al., 2020; Bilalis et al., 2019). There are two ways in which this crop can be used for human food: directly as food (after saponins have been removed) or processed (bread, cakes, and paste). Compared to wheat, quinoa contains two times more protein, making it one of the few non-meat proteins that is qualitatively and quantitatively superior to other plant proteins (Ceccato et al., 2011). Currently, as a result of the increased attention to quinoa as a highly nutritious crop and increased international demand, the cultivation of this crop is expanding in Greece (Noulas et al., 2017; Bilalis et al., 2019). This study aimed to investigate all greenhouse gas emissions generated by quinoa seed production in Greece and their relationship with farm-related factors, from fertilizer production to energy consumption for all cultivation techniques.

MATERIALS AND METHODS

The amount of all GHG emissions was estimated using Cool Farm Tool software which was developed by Cool Farm Alliance (Grantham, Lincolnshire, UK) as a calculating tool to estimate greenhouse gas emissions and carbon footprint based on yield and marketable yields in a field, crop area, fertilizer application (type and rate), and energy use (use of electricity and fuel). In general, the Cool Farm Tool provides immediate results and the ability to run “what – if” scenarios, and also covers nearly all crops worldwide, with the exception of crops grown in non-soil media (e.g., greenhouses or hydroponic systems).

Collection and Analysis

In order to collect data, a questionnaire including questions regarding cultivation details, soil characteristics, inputs and fuel, use was distributed and completed by forty (40) quinoa producers from Central Greece during the 2023 spring growing season. In all studied fields, quinoa was cultivated as rainfed and was not treated with any pesticide during its growing period. Excessive values were excluded from the results in order to calculate the mean value and minimize error. Finally, in the present study, the greenhouse gases (GHG: CO₂, CH₄, and N₂O) were expressed as kilograms of CO₂ equivalent (kg CO₂-eq) (Folina et al., 2021).

Input Data and Parameters

For data collection, a questionnaire divided into four categories/groups (cultivation details, soil characteristics, inputs and fuel) was distributed to quinoa producers.

- **Group 1** contained information regarding the cultivation area and amount of final product. The data on waste management was also provided to Group 1. A unanimous decision was reached by the producers regarding the

management of the residues. It was either distributed on the plot, or it was integrated or used as a cover with the crop residues.

- **Group 2** recorded soil characteristics such as soil texture (clay, silty, sandy, etc.), soil organic matter. The soil moisture was described as "dry", and the soil drainage as "good". In addition, the pH of the soil was also determined.
- **Group 3** included fertilization methods. In particular, the type of fertilizer used, its application dose, and the evaluation of the measure (fertilizer units or products) were selected.
- **Group 4** recorded direct energy use, i.e., the energy source was selected and the amount of energy (liters) used for the crop was entered. The consumption of each task was recorded separately (plowing, cultivator, harrowing, sowing, fertilization, plant protection, irrigation, supervision visits, and harvesting).



Figure 1: Experimental field of quinoa

RESULTS AND DISCUSSIONS

The results of greenhouse gas emissions of quinoa production expressed as CO₂-eq are presented in Table 1. Based on a mean area of 3.57 ha and 2451.9 kg of quinoa produced seed per hectare, the estimated total carbon footprint of quinoa cultivation was 4,187.31 kg CO₂-eq. Accordingly, the estimated carbon footprint values per hectare and per kilogram of quinoa seed were 1,159.65 and 0.48 kg CO₂-eq, respectively. In addition, based on a mean protein content of 12.87% and, consequently, on a protein yield of 315.55 kg ha⁻¹, the total CO₂-eq emissions per kilogram of protein was found to be 3.68 kg (Table 1).

Table 1. Greenhouse gas emissions of quinoa cultivation expressed as CO₂-eq

Total CO ₂ -eq emissions (kg)*	Total CO ₂ -eq emissions per ha (kg)	Total CO ₂ -eq emissions per kilogram of seed product (kg)	Total CO ₂ -eq emissions per kilogram of protein (kg)
4187.31	1159.65	0.48	3.68

*The total CO₂-eq emissions come from an average value of 3.57 ha

As can be seen from the analysis of CO₂-eq emissions per hectare (Figure 2), the emissions from the production of fertilizers, the application of fertilizers, the energy use (fuel consumption), and the residue management were the main contributors and were emitted as 471.93 kg (40.38%), 350.00 kg (30.35%), 288.68 kg (24.59%), and 49.04 kg (4.18%), respectively. The use of nitrogen (N) and phosphorus (P) in quinoa production is variable in the sample,

with average amounts of 147 and 89 kg ha⁻¹, respectively. All of the farmers use a tractor and a threshing machinery. Total fuel consumption for tractors (land and planting preparation) is 85 liters ha⁻¹ on average and for threshing machinery 35 liters ha⁻¹. In addition, all the fields of the present study were rainfed and no pesticides were used according to the farmers. The above-mentioned results are in line with those of Gamboa et al. (2020) and Lotfalian Dehkordi and Forootan (2020), who reported that the fertilizers (production and application) and energy use for land and planting preparation are the main sources of GHs emissions in quinoa cultivation, and recommended that it is possible to achieve sustainable agriculture and a healthier environment through the application of advanced machinery, the management of fertilizers, and the use of renewable fuels.

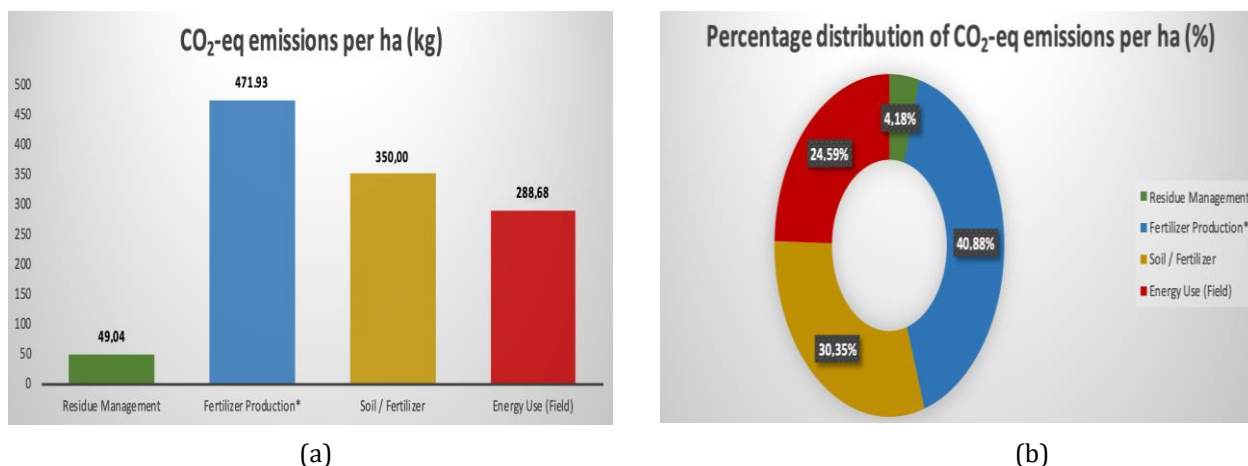


Figure 2. (a) CO₂-eq emissions per hectare (kg) for residue management, fertilizer production, fertilizer application (soil/fertilizer) and energy use in field. (b) Percentage distribution of CO₂-eq emissions per hectare (%) for residue management, fertilizer production, fertilizer application (soil/fertilizer) and energy use in field. *Calculated with valid preset values for fertilizer production.

Likewise, fertilizer production is also associated with the highest emissions of CO₂-eq per kilogram of seed product, which amounts to 0.34 kg (Figure 3a), which accounts for 40.53% of the total GHGs emissions per kilogram of product (Figure 3b). In addition, fertilizer application was responsible for 0.15 kg CO₂-eq per kilogram of seed (30.18%), energy use for 0.12 kg CO₂-eq (which accounted for 25.15% of the total emissions per kilogram of product) and residue management for 0.02 kg CO₂-eq per kilogram of seed (4.14%).

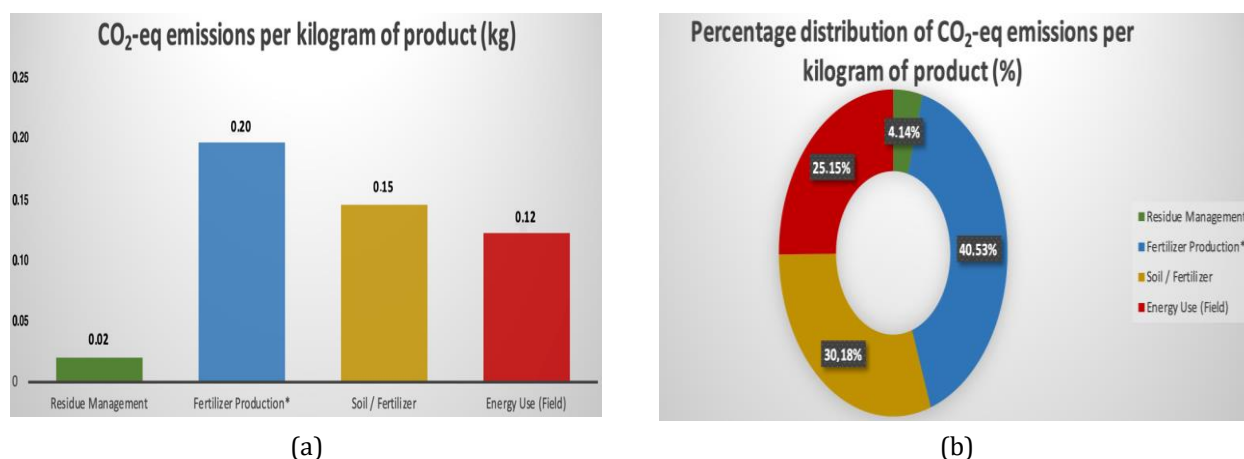


Figure 3. (a) CO₂-eq emissions per kilogram of seed product (kg) for residue management, fertilizer production, fertilizer application (soil/fertilizer) and energy use in field. (b) Percentage distribution of CO₂-eq emissions per kilogram of seed product (%) for residue management, fertilizer production, fertilizer application (soil/fertilizer) and energy use in field. *Calculated with valid preset values for fertilizer production.

As for the analysis of CO₂-eq emissions per kilogram of protein and its percentage distribution, these traits presented similar trends as described in CO₂-eq emissions per kilogram of product, where the emissions from the fertilizer production, the fertilizer application, the energy use, and the residue management were the main contributors and emitted as 1.50 kg (41%), 1.11 kg (30%), 0.91 kg (25%), and 0.16 kg (4%), respectively. In the present study, the total CO₂-eq emissions per kilogram of protein (3.68 kg) are lower in comparison with other grains such as wheat (4.51 kg), barley (5.33 kg) and maize (6.70 kg), which implies that quinoa, due to its high protein content and low greenhouse gas emissions, could be an excellent substitute and gluten-free alternative to cereal grains and make an important contribution to more sustainable food security in the world (Clune et al., 2017).

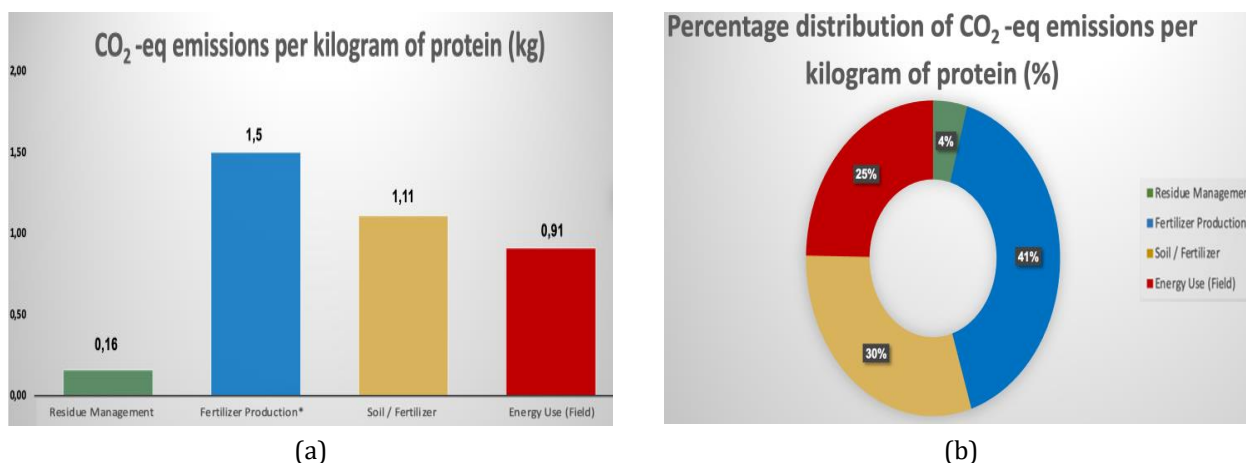


Figure 4. (a) CO₂-eq emissions per kilogram of protein (kg) for residue management, fertilizer production, fertilizer application (soil/fertilizer) and energy use in field. (b) Percentage distribution of CO₂-eq emissions per kilogram of protein (%) for residue management, fertilizer production, fertilizer application (soil/fertilizer) and energy use in field. *Calculated with valid preset values for fertilizer production.

CONCLUSIONS

Consequently, attention must be given for the mitigation of the environmental impact of quinoa seed production. Our results entail some recommendations for improving the eco-efficiency of quinoa seed production in Greece. The intensity of soil tillage is an important factor in greenhouse gas emissions. Conventional tillage intensifies this problem through frequent ploughing, which leads to the release of GHGs. In recent years, more and more producers worldwide have chosen to minimum tillage or even no tillage worldwide. As for fertilization, the excessive use of fertilizers leads to the accumulation of nutrients in the soil, resulting in an inability to be absorbed and utilized by the plants and ultimately in their leaching and evaporation. The use of new type fertilizers (e.g., with inhibitors) can result in higher nitrogen use efficiency, and can gradually reduce nitrogen leaching and lower GHG emissions. Moreover, concerning the irrigated fields, drip irrigation system can significantly reduce greenhouse gas emissions. The use of crop rotation systems can reduce chemical fertilizers use and consequently GHGs footprints. The use of renewable energy sources also leads to GHGs emissions reduction. In addition, the use of organic fertilizers leads to soil improvement and the induction of microbial activity; these help to reduce leaching of nutrients from the soil, resulting in reduced losses. Finally, agricultural practices that aim to capture carbon, can avoid future greenhouse gas emissions and reduce greenhouse gas emissions resulting from agricultural operations

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Conflicts of Interest

The authors declare that they do not have any conflict of interest.

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