Assessment of the Multiannual Impact of the Grape Training System on GHG Emissions in North Tajikistan

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Abstract: The overarching goal of agricultural sciences is to optimize production technology to rationalize the use of production resources, energy, and space. Due to its high fertilization and water requirements, the vine is a plant with a high potential for greenhouse gas (GHG) emissions. The modifying factor in the production technology is plantation management. To reach the assumed goal, a field experiment was conducted in the years 2001–2020, and the following training systems were used: multi-arm fan system (A) trunk height <30 cm, (B) 80 cm, (C) 120 cm, one-side multi-arm, paired planting (D) 120 cm, (E) 140 cm. The total amount of GHGs emitted in vine cultivation was calculated according to ISO 14040 and ISO 14044 standards. The system boundaries were: establishing the plantation, the production and use of fertilizers and pesticides, energy consumption for agricultural treatments, and gas emissions from the soil. The amount of GHG emissions for cultivation using the systems A, B, C ranged from 426.77 to 556.34 kg of CO\textsubscript{2}-eq Mg of yield\textsuperscript{−1}, while in the case of D and E systems, the value was approx. 304.37 to 306.23 CO\textsubscript{2}-eq Mg of yield\textsuperscript{−1}. When comparing this stage with total annual emissions related to cultivation (for 1 ha), the amount of emitted GHGs at this stage is from approx. 42% to 58% higher than from annual emission related to cultivation. Concrete poles are the main element related with GHG emission during stage of plantation establishment, from 97 to 98% of emission. In the case of annual production, nitrogen fertilizers are responsible for approx. 36%. Moreover, the results show that systems D and E increased the average annual fruit yield (per 19 years of research) by approx. 68% compared to the A, B, C systems. There was no difference in the yield of plants with different height of shoots in the D and E systems. The “one-side, multi-arm, paired planting system” was characterized by the highest production and environmental efficiency.

Keywords: GHG; management; training system; carbon cycle; grape yield
1. Introduction

A strategic element of modern agriculture is the rational use of means of production in the context of sustainable development. The most important aspect of agricultural optimization is reducing its environmental impact, especially in the context of GHG emissions. Introducing production methods that efficiently use water, energy, and soil resources follows the principles of the most prominent quality management systems in primary production [1,2]. Appropriate management of plant production in terms of fertilization, protection, and irrigation can result in obtaining crops with limited energy consumption, which is associated with a reduced level of GHG emissions. Grapes are grown primarily in areas with favorable climatic conditions, the most important of which are the temperatures during the growing season and the level of insolation [3]. These parameters have a critical impact on the content of active substances in the fruit, which determines their taste and suitability for the winemaking process [4]. Topalović et al. [5] reported that the climatic conditions and the level of irrigation significantly impacted the content of beneficial compounds in grape skins. De Oliveira et al. [6] obtained similar results for grapes grown under different climatic conditions in Brazil. A frequent consequence of these specific requirements of grapes is the organization of their cultivation in mountainous regions with poor soils, requiring irrigation. Effective fertilization in such soils is difficult due to the high risk of leaching nutrients due to the water used for irrigation [7,8]. Mountain soils are usually characterized by a small capacity of the sorption complex, which additionally makes it difficult to rationalize the use of means of production. Vineyards are often planted on the slopes in order to maximize the plants’ use of insolation. Cultivation in such conditions requires more means of production than cultivation in fertile soils with high agricultural value. Vineyards are mostly located in areas with poorly developed agriculture, which further intensifies the problem of the global negative impact of vine cultivation on the natural environment [9]. Primitive agricultural areas with unfavorable farming conditions are characterized by a particularly high potential to implement measures limiting the negative environmental impact of agriculture. Therefore, even small changes in the cultivation technology can prove beneficial, reducing the level of GHG emissions per area unit or mass unit of produce [10,11].

Today, agricultural production quality systems increasingly focus on the environmental impact of agriculture. iticulture is an element of an extensive supply chain in the world related to the supply of fresh and processed products [12], the emerging market awareness of consumers in the field of environmental and health effects of food production forces producers to optimize production in the above-mentioned areas [13–15]. Currently, the most important aspect of agricultural optimization is reducing its environmental impact, especially in the context of GHG emissions. Sustainable land management also allows biodiversity conservation and, at times, ecological restoration. Therefore, in the global production of wine raw materials, there are many private quality management systems, which focus not only on the technological quality of fruit but also on environmental and social issues [9–16].

The most frequently used indicator for assessing the level of environmental impact of agriculture is the carbon footprint. Global GHG emissions from fossil fuels used in agriculture are estimated to be approx. 0.4–0.6 Gt of CO$_2$-eq year$^{-1}$, while total GHG emissions from agriculture are estimated to be 4.6 Gt of CO$_2$-eq year$^{-1}$ [17]. One of the most important elements comprising the boundary of a carbon footprint calculation system is energy consumption. In the calculation methodology, energy sources are divided into primary and secondary. The primary sources of emissions result from agricultural treatments on the farm (e.g., tillage, sowing, fertilization, harvesting and transport, irrigation). Secondary (indirect) emission sources include emissions from the production of fertilizers and pesticides, as well as production and maintenance of equipment, etc. What is significant from the point of view of generating the greenhouse effect is the emission of GHGs from agricultural soils: nitrogen oxides, carbon dioxide, and methane. The amount of nitrogen compounds emitted into the atmosphere is related to the fertilization efficiency and proper management.
of soil organic matter. Total \( \text{N}_2\text{O} \) emissions from fertilizers increased from 0.07 Gt CO\(_2\)-eq in 1961 to 0.68 Gt CO\(_2\)-eq in 2010 [17]. Nitric oxide (N\(_2\)O) is the key compound in generating the greenhouse effect.

The aim of the study was to assess the environmental impact of grape cultivation in various cultivation technologies. The indicator used to assess the environmental impact was the level of GHG emissions resulting from the vine production process. The modifying factor in the production technology was plantation management. The functional unit selected was 1 Mg of commercial yield of vine.

2. Materials and Methods

The calculation was performed based on results from an experiment conducted in the years 2001–2020 in northern Tajikistan, in Sughd Region, Ghafurov district (40°10′42″ N 69°42′30″ E). The climate of the region is dry and hot, characterized by an annual rainfall of approx. 223 mm (Table 1), with evaporation ranging from 1.188 to 1.573 mm and 2.000 to 5.000 of total annual heating degree days (°C) [18–20].

Table 1. Temperature and precipitations in Ghafurov region in 2001–2020.

|       | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| P (mm)| 15.1| 17.3| 39.6| 38.0| 33.4| 8.2 | 8.6 | 0.3 | 5.9 | 19.6| 18.7| 17.8|
| T (°C)| 2.3 | 4.2 | 11.2| 15.8| 22.5| 27.4| 29.6| 27.3| 22.8| 12.7| 7.4 | 1.8 |

P—precipitation, T—temperature.

A randomized block design was used to set up a single factor experiment. The Tayfi Pink variety was cultivated on Gypsic Calcisols [21]. The physical and chemical properties of the investigated soil are presented in Table 2.

Table 2. Physical and chemical properties of investigated soil.

| Soil Layer (cm) | pH | C Org% | N | P | K | Bulk Density, g cm\(^{-3}\) | Particle Density, g cm\(^{-3}\) |
|----------------|----|--------|---|---|---|-----------------------------|-----------------------------|
| 0–25           | 7.0| 0.49   | 365| 920| 1634| 1.58                        | 2.51                        |
| 25–50          | 6.9| 0.25   | 243| 696| 1722| 1.89                        | 2.61                        |
| 50–75          | 6.9| 0.17   | 181| 599| 1812| 1.92                        | 2.62                        |
| 75–100         | 6.7| 0.08   | 1176| 541| 1731| 2.01                        | 2.36                        |

A vineyard training system was the experimental factor. Soil and climate conditions in all variants were the same. The area of each plot was 0.10 ha, and each treatment was repeated three times. The five different schemes of training systems are presented in Table 3. In the experiment, fertilization was used in the following doses: 200 kg N ha\(^{-1}\) ammonium nitrate (34% N), 100 kg P ha\(^{-1}\) triple super phosphate (21% P), and 100 kg K ha\(^{-1}\) potassium chloride (50% K). The first dose of nitrogen was applied in early spring (50%) in March, and the second dose (50%) was applied at the end of the may during the blooming period. Phosphorus was applied in late autumn (in one dose in November). The first dose (50%) of potassium was applied in late autumn and the second dose was applied in May with a second dose of nitrogen. Irrigation at the level 500–550 mm was applied each year, and the irrigation was performed on 6–7 dates. Formation pruning was carried out in November each year.

To calculate the amount of GHG emissions in grape production the ISO 14040:2006 “Environmental management—Life cycle assessment—Principles and frame-work” [22] standard was used. The calculation was based on data from 19 years of cultivation. The GHG emission was presented in carbon dioxide (CO\(_2\)) equivalent. The results were related to 1 Mg of the grape yield. The amount of GHG emissions (E kg Mg\(^{-1}\)) in carbon dioxide
equivalent was calculated according to the IPCC methodology [22,23] and according to the formula:

\[ E = \frac{e_{ec}}{\text{yield}} \]  

\[ e_{ec} = e_s + e_{chem} + e_{field} + e_{mm} + e_{irr} \]

where:

- \( e_s \) is the emission associated with manufacture of concrete poles, steel wires, and anchors used on the plantation;
- \( e_{chem} \) is the emissions associated with the manufacture of fertilizers and agrochemicals used for crop cultivation;
- \( e_{field} \) is the emissions from the field, direct and indirect emission, associated with synthetic fertilizers and manure use, mineralization of organic matter in the soil, and management of post-harvest residues and mineralization of organic matter in the soil [23,24];
- \( e_{mm} \) is emissions associated with field work at the farm;
- \( e_{irr} \) is emissions associated with irrigation (for irrigation, electric water pumps were used, emissions were calculated using the GHG emissions coefficient).

The value of nitric oxide emissions from harvesting residue and mineral fertilizers was adopted at 1.00% (ISO 14040; Sikora et al. 2020b). The value “N–N\(_2\)O emissions” was multiplied by 44/28 to convert it into N\(_2\)O. N\(_2\)O emissions were used as a CO\(_2\) equivalent by multiplying them by a global warming potential of 298. The adopted content of carbon fraction in dry matter of harvesting residue was 50%, the adopted mineralization rate of carbon from residue was 25%, and the adopted soil mineralization rate of organic matter was 2% [23,25]. System boundaries are presented in Figure 1. The description of inputs in the calculation is presented in Tables 4 and 5.

**Table 3. Training system description.**

| Training System | System Name                      | Spacing         | Plant Density ha\(^{-1}\) | Trunk Height |
|-----------------|----------------------------------|-----------------|---------------------------|--------------|
| A               | multi-arm fan system             | 3 × 2 m         | 1670                      | <30 cm       |
| B               | multi-arm fan system             | 3 × 2 m         | 1670                      | 80 cm        |
| C               | multi-arm fan system             | 3 × 2 m         | 1670                      | 120 cm       |
| D               | one-side, multi-arm, paired planting | 4 × 3.7 + 0.6 m, | 1250                      | 120 cm       |
| E               | one-side, multi-arm, paired planting | 4 × 3.7 + 0.6 m, | 1250                      | 140 cm       |

**Figure 1.** System boundary.

**VINEYARD PLANTING**
- deep tillage
- manure fertilisation
- pole and wire positioning
- vine planting
- irrigation system
- material transport
- vineyard binding

**ANNUAL PRODUCTION**
- tillage
- mineral fertilisation
- irrigation
- weed and pest management
- harvesting
- material transport
### Table 4. Input data for vineyard planting.

| Training System                  | A    | B    | C    | D    | E    |
|----------------------------------|------|------|------|------|------|
| **Concrete poles [26,27]**       | 17.82| 476  | 612  | 612  | 676  | 676  |
| **Steel wires and anchors [28]** | 1.85 | 66.4 | 64.8 | 64.8 | 31.2 | 31.2 |
| **Input (Diesel) [29]**          |      |      |      |      |      |      |
| Deep tillage                     | 2.68 | 40.0 | 40.0 | 40.0 | 40.0 | 40.0 |
| Manure spreading                 | 2.68 | 17.8 | 17.8 | 17.8 | 17.8 | 17.8 |
| Manure covering                  | 2.68 | 24.0 | 24.0 | 24.0 | 24.0 | 24.0 |
| Digging holes                    | 2.68 | 27.6 | 35.5 | 35.5 | 39.2 | 39.2 |
| Transport, pole and wire positioning, planting | 2.68 | 4.1  | 6.0  | 6.0  | 7.0  | 7.0  |
| Irrigation system preparation    | 2.68 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 |

### Table 5. Input data for annual production.

| Training System                  | A, B, C, D, E |
|----------------------------------|---------------|
| **Ammonium nitrate [30]**        | 9.28          |
| **Triple superphosphate [30]**   | 0.44          |
| **Potassium salt [30]**          | 0.68          |
| **Pesticides [31]**              | 10.97         |
| **Tillage, 2×**                  | 2.68          |
| **Mineral fertilization, 3×**    | 2.68          |
| **Plant protection, 4×**         | 2.68          |
| **Harvest and field transport**  | 2.68          |
| **Irrigation [32]**              | 4.6           |

### Statistical Analysis

The statistical software package Statistica v. 13.0 (StatSoft Inc. Tulsa, OK, USA) with ANOVA was applied to analyze the results. Tukey’s range test (at a significance level of $\alpha = 0.05$) was applied to test the significance of mean differences among the treatments.

### 3. Results and Discussion

Estimating the environmental and economic efficiency of the implemented quality systems in primary production is an essential element related to the evaluation of the actual impact of the rules for manufacturers regarding the quality of produce and the degree of environmental impact [33,34]. One of the methods of comprehensive and multifaceted assessment of the quality system is to determine the life cycle of products, taking into account the use of energy and means of production, as well as renewable and non-renewable environmental resources [35,36]. However, the development of a reliable and universal method is very difficult. Farms operate in a specific climate, as well as in economic and social contexts, which significantly affects the assessment and virtually prevents its inter-
The presented work compares the total GHG emissions for various vine cultivation methods within the limits of the evaluation system adopted at the emission source inventory stage. An essential aspect of the research is the timeline, which has been set at 19 years.

3.1. Yield

The results of the conducted research indicate that the applied systems significantly impacted the yield. Figure 2 shows the average yields for the years 2005–2020. The first four years of cultivation were characterized by limited yields and significant vegetative development of plants, which is related to the natural development of this species. In 2005, the plants produced their first commercial crop. The highest yields were recorded in the “D” and “E” systems and the lowest in the “A” system. In addition to the lower stocking densities, the “D” and “E” variants were high-trained, the “C” variant was also classified as a high-trained system, while the “A” and “B” variants were classified as low-trained. There were no statistically significant differences between the “D” and “E” systems. “D” and “E” systems yielded an average of 5.5 tonnes of the crop more than in the “C” variant, 8.2 tonnes more than the “B” variant, and approx. 8.7 tonnes more than in the “A” variant. Studies by various authors [38,39] indicate that in systems with low training, with the downward positioning of shoots, the vigor of plants and yield are reduced compared to high training systems. According to Van Leeuwen et al. [40], vineyards with a wider row spacing show better adaptation to dry conditions. The presented position is related to the assumption that with a lower stocking density, each plant has easier access to water and nutrients in the soil and makes better use of insolation. This position is justified when the vine roots fully permeate the soil [14,41]. In the presented research, the development area of a plant for variants “A”, “B”, and “C” was 6 m², while for variants “D” and “E”, it was 7.4 m².

![Figure 2](image_url)

**Figure 2.** Average yield of fresh fruit per training system (A, B, C, D, E) in the years 2005–2020. 

1 Means with different letters are significantly different, according to Tukey test \((p \leq 0.05)\).
3.2. GHG Emission

Alaphilippe et al. [42] pay attention to the significance of the adopted time limit in the life cycle assessment for perennial plants. In a single-year time frame, it is difficult to take into account the level of GHG emissions related to the establishment of the plantation and its operation during the period of vegetative development of plants. Bessou et al. [43] drew similar conclusions. Taking into account the methodological recommendations in the above-cited literature references, the correct approach to determining the time frame of the life cycle calculation system should take into account the entire production cycle of perennial plants. However, obtaining multi-annual data is problematic and often even impossible. Moreover, with this approach, the final results can only be obtained after the plantation is liquidated. However, for the purposes of assessing the environmental effectiveness of the modifications to the production technology, the system boundary should include the entire life cycle of the vine on the plantation, from planting to liquidation.

The results of the experiment show a large differentiation in the level of energy consumption and GHG emissions in individual plant cultivation strategies. In the case of vines, the stage of establishing a plantation is important from the point of view of GHG emissions due to the high consumption of construction materials such as concrete and steel. In the case of the studied plant maintenance systems, the value of GHG emissions related to the establishment of plantations ranged from 9291.9 to 12881.7 kg CO$_2$ per 1 ha, depending on the adopted cultivation technology (Table 6). The lowest value of this parameter was found in the “A” system cultivation, while the highest GHG emissions were calculated for the establishment of a plantation in the “D” and “E” systems. The differences in GHG emissions resulted from the amount of concrete and steel used to support the plants. Table 7 presents the values related to the annual vine production. The inputs and related emissions for each system were identical, the only differentiating factor was the yield affecting the biomass remaining in the field: emissions related to organic matter mineralization. Taking into account the nineteen-year cultivation cycle, the value of this parameter, which includes the stages of establishing and cultivation per 1 year, the stage of establishing a plantation generated GHG emissions ranging from 43.37 to 67.13 kg CO$_2$-eq Mg year$^{-1}$ (Table 8). From the environmental point of view, the highest efficiency was achieved in the facilities operating in the “D” and “E” systems, while the “B” system proved the least effective. At the stage of plantation establishment, the most important element generating the carbon footprint per unit area was the production of concrete poles and steel rods used as support for shoots. In the “D” and “E” system research objects, much higher yields were obtained, which impacted the results of calculations per unit mass of the product. Data presented in the scientific literature related to the calculation of the life cycle for grape production usually do not take into account the stage of establishing a plantation. Moreover, the adopted time frame is limited to one year [44,45]. This approach is in line with the methodology [22,46] and the error is systematic. However, the authors’ own research shows that the stage of establishing a plantation is important from the point of view of the level of GHG emissions. The total amount of emitted GHGs at this stage is from approx. 42% to 58% higher than the annual emission related with cultivation. Therefore, the omission of this element appears to be the wrong approach to assessing the life cycle of grape production.
### Table 6. Total GHG emissions associated with vineyard planting (kg CO$_2$-eq ha$^{-1}$).

| Training System | A     | B     | C     | D     | E     |
|-----------------|-------|-------|-------|-------|-------|
| Input           | kg CO$_2$-eq ha$^{-1}$ |
| Concrete poles  | 8482.32 | 10,905.84 | 10,905.84 | 12,046.32 | 12,046.32 |
| Steel wires and anchors | 64.8    | 64.8    | 64.8    | 31.2    | 31.2    |
| Deep tillage    | 63.84   | 63.84   | 63.84   | 63.84   | 63.84   |
| Manure spreading | 31.92   | 31.92   | 31.92   | 31.92   | 31.92   |
| Manure covering | 47.88   | 47.88   | 47.88   | 47.88   | 47.88   |
| Digging holes   | 88.12   | 113.30  | 113.30  | 125.14  | 125.14  |
| Transport, pole, and wire positioning | 13.09 | 19.15 | 19.15 | 22.34 | 22.34 |
| Irrigation system | 47.88   | 47.88   | 47.88   | 47.88   | 47.88   |
| N$_2$O–N emissions produced from managed soils, biomass, manure | 465.14 | 465.14 | 465.14 | 465.14 | 465.14 |
| Total           | 9304.99a | 11,759.75b | 11,759.75b | 12,881.66c | 12,881.66c |

1 Means with different letters are significantly different, according to Tukey test ($p \leq 0.05$).

### Table 7. Total GHG emissions associated with annual production (kg CO$_2$-eq ha$^{-1}$).

| Training System | A     | B     | C     | D     | E     |
|-----------------|-------|-------|-------|-------|-------|
| Input           | kg CO$_2$-eq ha$^{-1}$ |
| Ammonium nitrate | 1856.0 | 1856.0 | 1856.0 | 1856.0 | 1856.0 |
| Triple superphosphate | 100.4   | 100.4   | 100.4   | 100.4   | 100.4   |
| Potassium salt  | 81.9    | 81.9    | 81.9    | 81.9    | 81.9    |
| Pesticides      | 93.3    | 93.3    | 93.3    | 93.3    | 93.3    |
| Tillage, 2×     | 95.8    | 95.8    | 95.8    | 95.8    | 95.8    |
| Mineral fertilization, 3× | 55.5   | 55.5   | 55.5   | 55.5   | 55.5   |
| Plant protection, 4× | 98.9   | 98.9   | 98.9   | 98.9   | 98.9   |
| Harvest and field transport | 16.0   | 16.0   | 16.0   | 16.0   | 16.0   |
| Irrigation      | 95.8    | 95.8    | 95.8    | 95.8    | 95.8    |
| N$_2$O–N emissions produced from managed soils, biomass, fertilizers | 122.3 | 122.3 | 122.3 | 122.3 | 122.3 |
| Emissions related to organic matter mineralization(soil, crop residue) | 1003.6 | 1007.5 | 1028.3 | 1035.8 | 1035.1 |
| Total           | 3619.5a1 | 3623.4a | 3644.2b | 3651.7b | 3651.0b |

1 Means with different letters are significantly different, according to Tukey test ($p \leq 0.05$).

### Table 8. Table GHG emissions associated with vineyard planting calculated for 1 Mg of yield; values of GHG emission have been spread over the period 2001–2020 (kg CO$_2$-eq Mg of yield$^{-1}$).

| Training System | A     | B     | C     | D     | E     |
|-----------------|-------|-------|-------|-------|-------|
| Input           | kg CO$_2$-eq Mg of yield$^{-1}$ |
| Concrete poles  | 46.90  | 57.28  | 45.22  | 34.74  | 34.98  |
| Steel wires and anchors | 0.36    | 0.34    | 0.27    | 0.09    | 0.09    |
| Deep tillage    | 0.35   | 0.34    | 0.26    | 0.18    | 0.19    |
| Manure spreading | 0.18   | 0.17    | 0.13    | 0.09    | 0.09    |
| Manure covering | 0.26   | 0.25    | 0.20    | 0.14    | 0.14    |
| Digging holes   | 4.64   | 5.96   | 5.96   | 6.59   | 6.59    |
| Transport, pole, and wire positioning | 0.07 | 0.10 | 0.08 | 0.06 | 0.06 |
| Irrigation system | 0.26   | 0.25    | 0.20    | 0.14    | 0.14    |
| N$_2$O–N emissions produced from managed soils, biomass, manure | 2.57 | 2.44 | 1.93 | 1.34 | 1.35 |
| Total           | 55.59b1 | 67.13c | 54.25b | 43.37a | 43.63a |

1 Means with different letters are significantly different, according to Tukey test ($p \leq 0.05$).
The most important parameter impacting GHG emissions in the experiments was the size of crop yields. It was this parameter that had the greatest impact on the total GHG emissions in primary production. Table 9 presents the average annual GHG emission value, taking into account the annual amount of the means of production and treatment, as well as the stage of plantation establishment, all calculated per yield unit. In the proposed “D” and “E” plantation systems, better nitrogen use was identified, which translated into a lower carbon footprint (Table 7, N₂O–N emissions produced from managed soils, biomass, fertilizers). The value of GHG emissions in these systems was similar, amounting to 304.37 and 306.23 kg CO₂-eq Mg of commercial yield⁻¹, respectively (Figure 3). The highest value of the carbon footprint was found in the “A” system facility, where the value of this parameter was 556.34 kg CO₂-eq Mg of commercial yield⁻¹. Modification of the plant management method allowed the carbon footprint to be reduced by 43%. The average value of the carbon footprint for grape production in selected vineyards in France was 270 kg CO₂-eq per 1 Mg of fruit used as a raw material for wine production. These authors found that the burning of liquid fuels was the factor that most influenced GHG emissions in grape production. Nitrogen fertilization was negligible for the value of the discussed parameter. In our own research, the management of nitrogen fertilization generated almost half of the total production-related GHG emissions. The GHG emission values in the production of industrial grapes in Italy were 140 kg CO₂-eq Mg of yield⁻¹ [45]. However, these authors did not take into account fertilization and GHG emissions from the soil at the boundary of the system. Fertilization is one of the most important elements shaping the anthropopressure in agriculture. Vázquez-Rowe et al. [16] also confirmed this in their research on vineyards in Chile. According to the results of these authors, fertilization was the most important factor of GHG emission. Carbon footprint values for various grape varieties grown in the Valencia region ranged from 90 to 320 kg CO₂-eq Mg of yield⁻¹ [47]. Such a low GHG emission value resulted from the limited level of nitrogen fertilization related to the use of organic fertilization. These authors indicate a significant impact of the method of vineyard management on the production potential of plants. However, apart from introducing modifications to the plant management system, it is very important to assess the productive potential of the habitat to optimize fertilization and irrigation [48].

With the implementation of such measures, a several dozen percent improvement in the environmental efficiency of the production system can be achieved. Lištakas et al. [49], who calculated the carbon footprint of grapes growing in Cyprus, obtained results similar to those of the authors. These authors state that in the analyzed systems the value of GHG emissions resulting from the use of mineral fertilizers converted to CO₂ was approximately 200 kg Mg of yield. Another 100 kg resulted from N₂O emissions from the soil. These authors emphasize that the optimization of nitrogen fertilization is the most effective solution for reducing the impact of vine cultivation on climate warming.

The method of vineyard management most often results from the tradition in a given region. Therefore, the implementation of new production methods requires, first of all, a change in the mentality of producers, which is one of the biggest barriers to innovation of the agricultural area. The conducted research allowed for an environmental inventory of possible grapevine production technologies. The research used both the technologies that are the most popular in the area where the research was conducted and the technologies proposed by the authors, which were adapted to the climatic and soil conditions of North Tajikistan. The system boundary of the environmental impact assessment covered not only the annual consumption of the means of production, but also the process of establishing a plantation. The results of the research are a clear indication of the production methods that should be promoted in the research area. So far, such a thorough analysis of the assessment of the environmental impact of grapevine cultivation in North Tajikistan has not been carried out. The research results show a great potential for optimizing grapevine production technology in the context of improving environmental and production efficiency. The most frequently used methods of plantation management in the research area turned out to be ineffective in terms of the environment.
Table 9. Mean annual GHG emissions and energy consumption associated with agricultural treatments, fertilizers, pesticides, and vineyard planting calculated for 1 Mg of yield in period 2001–2020 (kg CO$_2$-eq Mg of yield$^{-1}$).

| Training System                  | A      | B      | C      | D      | E      |
|----------------------------------|--------|--------|--------|--------|--------|
| **Input**                        |        |        |        |        |        |
| Ammonium nitrate                 | 194.98 | 185.23 | 146.23 | 101.70 | 102.40 |
| Triple superphosphate            | 10.54  | 10.02  | 7.91   | 5.50   | 5.54   |
| Potassium salt                   | 8.61   | 8.18   | 6.46   | 4.49   | 4.52   |
| Pesticides                       | 9.80   | 9.31   | 7.35   | 5.11   | 5.15   |
| Tillage, 2×                      | 10.06  | 9.56   | 7.54   | 5.25   | 5.28   |
| Mineral fertilization, 3×        | 12.84  | 12.20  | 9.63   | 6.70   | 6.75   |
| Plant protection, 4×             | 105.43 | 100.55 | 81.02  | 56.76  | 57.11  |
| Harvest and field transport      | 42.98  | 41.39  | 35.03  | 27.76  | 27.88  |
| Irrigation                       | 12.8   | 12.2   | 9.6    | 6.7    | 6.7    |
| N$_2$O–N emissions produced from managed soils, biomass, fertilizers | 105.4  | 100.5  | 81.0   | 56.7   | 57.1   |
| Emissions related to organic matter mineralization (soil, crop residue) | 42.9   | 41.3   | 35.0   | 27.7   | 27.8   |
| Total                            | 556.34c | 530.44c | 426.77b | 304.37a | 306.23a |

1 Means with different letters are significantly different, according to Tukey test ($p \leq 0.05$).

Figure 3. Average GHG emissions per 1 Mg of fresh fruit yield per training system (A, B, C, D, E).  
1 Means with different letters are significantly different, according to Tukey test ($p \leq 0.05$).

4. Conclusions

The conducted analysis allowed the optimal system to be distinguished, both in terms of production potential and environmental impact. The main elements determining the intensity of GHG emissions have been cataloged.

1. A one-side, multi-arm, paired system (D, E) resulted in an increase in fruit yield by approx. 68% compared to the multi-arm fan systems.
2. In the case of the multi-arm fan system, the impact of the height of trunk on the yield was identified. In the case of the one-side method, there was no effect of the height of trunk on the yield of plants.
3. The amount of GHG emissions for the multi-arm fan system (A, B, C) ranged from 426.77 to 556.34 kg of CO$_2$-eq Mg of yield$^{-1}$, while in the case of the one-side, multi-arm, paired vine (D, E), the value was approx. 304.37 to 306.23 CO$_2$-eq Mg of yield$^{-1}$.

4. The plantation establishing stage should be included in the life cycle assessment for vine cultivation. The amount of emitted GHGs at this stage is from approx. 42% to 58% higher than annual emission related with cultivation.

5. From the point of view of environmental and production efficiency, the best method of growing grapevines was one-side, multi-arm, paired planting. This technology should be promoted in new grape plantations in Tajikistan.

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