



Investigating the Nexus Between GHG Emissions and AFOLU Activities: New Insights from C-Vine Copula Approach

Parisa Pakrooh¹ · Muhamad Abdul Kamal² · Cosimo Magazzino³

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Abstract The greenhouse gas (GHG) emissions from agriculture, forestry, and other land use (AFOLU) account for more than 10% of the total GHG emissions in Iran. To reduce the environmental impact, assessments of Iran's GHG emissions status are critical for identifying the national policies to achieve Sustainable Development Goals (SDGs) in the bio-based industry. However, there is no study exploring the dependency between AFOLU and GHG emissions in Iran by using the Vine Copula approach. Hence, the study aims to examine the causality direction and correlation structure among selected horticulture, farming crops, livestock, and poultry products and carbon dioxide (CO₂), nitrogen dioxide (N₂O), and methane emissions (CH₄) in the Iranian agriculture sector over the period 1961–2019, to determine which crops or products are more responsible to deteriorate the environment. The empirical strategy used a C-Vine Copula model to measure the correlations together with the Granger causality (GC) test to analyze the causality links. According to the empirical findings, several crops and products are the sources of emissions. Rice and vegetable cultivations, as well as meat and milk products (Kendall's τ values of 0.37, 0.33, 0.31, and 0.31, respectively), are the leading sources of CH₄ emissions. Legumes, eggs, maize, rice, and milk enhance N₂O emissions, while CO₂ emissions are caused by apple, potato, and apricot crops (Kendall's τ values of 0.22, 0.18, and 0.16, respectively). Finally, based on the findings, policy implications are offered.

Keywords Agricultural sector · Environmental impact · AFOLU · Copula function · Greenhouse gas · Iran

Introduction

Greenhouse gas (GHG) emissions have increased substantially in recent years with the expansion of activities, exacerbating global warming [25, 27]. Changes in average temperature and precipitation around the world as a result of climate change are referred to as global warming [28, 30]. Human activities and natural resources are the primary causes of climate change. Among all activities, agricultural, forestry, and other land-use (AFOLU) emissions are the second-largest contributor to overall GHG emissions. An increase in the concentration of carbon dioxide (CO₂), nitrogen dioxide (N₂O), and methane emissions (CH₄) in the atmosphere account for 14–30% of worldwide GHG emissions [14, 18, 19].

Asian countries account for the majority of AFOLU activity. Iran is one of the world's most advantageous

✉ Cosimo Magazzino
cosimo.magazzino@uniroma3.it

Parisa Pakrooh
parisa.pakrooh@feem.it

Muhamad Abdul Kamal
kamal@awkum.edu.pk

¹ Fondazione ENI Enrico Mattei, Milan, Italy

² Department of Economics, Abdul Wali Khan University Mardan, Mardan, Pakistan

³ Department of Political Science, Roma Tre University, Rome, Italy

agricultural locations, and as a consequence of enhanced AFOLU activities, it contributes to global warming. Assessments of Iran's agricultural activities emphasize the sector's importance in terms of job creation, food security, and international trade. In 2018, the sector accounted for roughly 16% of the overall GDP and 20 percent of total employment. Due to large farming programs, rising food demand, and the production of export-based goods, this sector is rapidly growing. Crop and livestock production accounts for a large portion of Iran's GDP, with crop production increasing from 50 to 191 tons per hectare and animal activity increasing tenfold from 1961 to 2019. From the standpoint of the environment, AFOLU activities account for more than 10% of total GHG emissions, which climbed from 18,244 to 75,973 Gigagrams during the period. The trend of overall agricultural yields, animal production, and other types of GHG emissions by Iran's AFOLU activities is depicted in Fig. 1 (in the Supplementary Materials). The sector's overall GHG emissions comprise both direct and indirect emissions from natural sources as well as anthropogenic activities. Before 1990, CH₄ emissions accounted for almost half of all GHG emissions, with CO₂ emissions gradually increasing as the use of fossil fuels in crop production systems expanded. Enteric fermentation of animal production and manure management on soil accounted for about 78 percent of total CH₄ and half of the total N₂O emissions, while the rest was attributed to energy sources, burning crops and savanna, and synthetic fertilizer. N₂O emissions have been steady at roughly 30% [7, 13, 17, 23, 33].

In brief, the country is very concerned about increasing GHG emissions intensity, particularly in the crop subsector, which is critical to human life and is closely linked to Sustainable Development Goals (SDGs). On the other hand, livestock and poultry-related activities are the second dominant source of GHG emissions (specifically CH₄) in Iran. As the demand for different kinds of meat and other animal products increases in developing countries, it is expected to double in the next decades. So, livestock and poultry-related activities have become one of the key factors of global GHG emissions mitigation efforts. As a result, it seems important to investigate the dependency structure and causality directions between agricultural and GHG components in Iran, as this action will assist policymakers in making successful sustainable agricultural policies. The assessment of GHG emissions from various agricultural activities could help the country in identifying chances of both handling food security and curbing down the ecological footprint. Numerous studies have addressed the importance of inspecting AFOLU activities and GHG emissions in order to mitigate emissions. [2, 3, 6, 11, 12, 15, 22, 29, 31, 32, 36–38, 40, 41] focused on the relationship between AFOLU operations and GHG

emissions. However, these studies merely examined the association between the variables, without looking into the specifics of the interaction between commodities and pollutants. According to [9], there is a need for more research into the intricate interactions of agricultural different activities and GHG emissions in the near future, as different activities and productions are accountable for different pollutants and emissions from AFOLU operations. Few studies consider the causality directions between GHG emissions and sustainable development of crop farming, horticulture, livestock, and poultry products. According to our knowledge, there is not very much research on the interactions of GHG and AFOLU components in the Iranian case. Moreover, the relationship between AFOLU activities and GHG emissions has been investigated by using standard statistics or econometric approaches. Alternative methodological strategies that overcome the disadvantages of using linear methods may model the dependency structure by using Copulas methods, particularly Vine Copulas for high dimensions. Therefore, a research gap emerges.

In the context of global warming, the agriculture sector of Iran is particularly relevant since it contributes to GHG emissions in a variety of ways and cannot be incompatible with the UNFCCC's (United Nations Framework Convention on Climate Change) goal of constant food security. Thus, resolving the "GHG-food" nexus is a key pillar of government policies aimed at constraining the GHG peak and delivering GHG neutrality. Therefore, understanding Iran's GHG emissions status is critical for identifying the national targets for emissions mitigation in the agriculture sector concerning the Nationally Determined Contributions (NDCs).

The main goal of this research is to examine the structural dependence and causal relationship between AFOLU activities and GHG emissions in the Iranian agriculture sector. It will help us to uncover why GHG emissions continue to rise, and how agriculture changes the environment. That is, comprehending the causal relationship might help us to forecast how farming operations affect climate change, as well as identify which crops or products are most linked with emissions. This type of research is critical for Iran since the country is vulnerable to global warming, and it can serve as a baseline for environmentalists engaged in reducing GHG emissions. The study is expected to contribute to the recent literature in various ways and its empirical findings shed light on the effects of GHG drivers from AFOLU components. The empirical findings provide comprehensive and useful information for governments to improve agricultural production in a more sustainable way by identifying specific and feasible mitigation options.

Materials and Methods

Estimation Procedures

According to the aim of the study, the estimation process is carried out in several stages. The initial step concerns the analysis of the stationary properties of the series, which is performed through the Augmented Dickey–Fuller (ADF) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) unit root tests. Then, the lag order dimension is assessed, as an important practical issue for the implementation of the causality tests. Consequently, the causality analysis is run through the GC test. Finally, the last part belonged to the correlation measurement and Copula approach. The approach is used to describe the dependency or link between product and pollutant.

The ADF test is based on the Auto-Regressive Moving Average (ARMA) process (first-order auto-regression), introduced by [5]. The null hypothesis of the test is the existence of a unit root in the series ($H_0: \phi = 1$). According to the calculated statistic and critical values for the distribution, the decision on stationarity is made. Equation (1) is based on the model of the ARMA process that is used to meet the stationary hypothesis:

$$y_t = \phi y_{t-1} + \varepsilon_t, \text{ with } t = 1, \dots, t \tag{1}$$

where y_t , ϕ , ε_t are the variable, AR parameter, and White Noise residuals, respectively [1].

For the KPSS stationary test, the stationary status is considered under the null hypothesis, and the alternative hypothesis is the evidence of an I(1) series. Like the ADF test, the decision is made through critical and calculated statistical values. If the critical value is higher than the calculated statistics, the series has a unit root [21]. The test is calculated as the sum of a deterministic trend (d_t), random walk (r_t), and stationary random error (ε_t), like Eq. (2).

$$\begin{aligned} y_t &= d_t + r_t + \varepsilon_t \\ r_t &= r_{t-1} + u_t \end{aligned} \tag{2}$$

GC test statistics are very sensitive to the lag length in the model. Given that, the optimal lag length is chosen according to the AIC (Akaike Information Criterion) and SBIC (Schwarz–Bayesian Information Criterion). Equation (3) is the general form of VECM for the variables, where $\Delta = (1-L)$, and L are the first difference and lag operators; c and β are the short- and long-term model coefficients. Then, the Granger causality test is applied to discover the causality flows between variables. This technique allows us to examine the relationship between production and GHG emissions (CO_2 , N_2O , CH_4).

According to the value of the F test, the decision on causality is made [24].

$$\begin{aligned} (1-L) \begin{bmatrix} \text{CO}_{2t} \\ \text{CH}_{4t} \\ \text{N}_2\text{O}_t \\ \text{Pr}_t \end{bmatrix} &= \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} \\ + \sum_{p=1}^P (1-L) \begin{bmatrix} c_{11i} & c_{12i} & c_{13i} & c_{14i} \\ c_{21i} & c_{22i} & c_{23i} & c_{24i} \\ c_{31i} & c_{32i} & c_{33i} & c_{34i} \\ c_{41i} & c_{42i} & c_{43i} & c_{44i} \end{bmatrix} \begin{bmatrix} \text{CO}_{2t-1} \\ \text{CH}_{4t-1} \\ \text{N}_2\text{O}_{t-1} \\ \text{Pr}_{t-1} \end{bmatrix} \\ + \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \end{bmatrix} [\text{ETC}_{t-1}] &+ \begin{bmatrix} u_{1,t} \\ u_{2,t} \\ u_{3,t} \\ u_{4,t} \end{bmatrix} \end{aligned} \tag{3}$$

$$\begin{aligned} H_0 : c_{11i} = c_{12i} = c_{13i} = c_{14i} = c_{21i} = c_{22i} \\ = c_{23i} = c_{24i} = c_{31i} = c_{32i} = c_{33i} \\ = c_{34i} = c_{41i} = c_{42i} = c_{43i} = c_{44i} = 0 \end{aligned} \tag{4}$$

$$\begin{aligned} H_a : c_{11i} \neq c_{12i} \neq c_{13i} \neq c_{14i} \neq c_{21i} \neq c_{22i} \neq c_{23i} \\ \neq c_{24i} \neq c_{31i} \neq c_{32i} \neq c_{33i} \neq c_{34i} \neq c_{41i} \\ \neq c_{42i} \neq c_{43i} \neq c_{44i} \neq 0 \end{aligned}$$

Many studies use correlation analysis to understand and quantify the degree of association between study variables, particularly in economics research. A coefficient of correlation is a single number that tells us to what extent two variables are related. However, correlation does not imply causality. It ranges between -1 and 1 , with a zero correlation showing no co-movement. Linear correlation analyses such as Pearson’s and Spearman’s correlation coefficients are simple tools to measure the dependence. Vine Copulas approach enables us to assess the complexity of the structure of dependencies among variables.

The early form of the Copula, which was introduced by [1], can measure bivariate dependency and is not able to model more than two dimensions. Moreover, they are a flexible tool for multivariate non-Gaussian distributions [8, 16, 34, 35].

There are various ways to model the structural dependence between GHG emissions and AFOLU-related activities, but due to the limitation of simple linear correlation coefficients, high flexibility of Copula functions to find the distribution of correlation without linear correlation assumption, estimating marginal distribution, providing information about density and structure of the

dependency, we apply the Copula function to measure the correlations.

Based on [], the joint structure of two continuous random variables with their marginal distributions can be measured by the Copula function. The function can connect marginal distributions without limiting the margin distribution. Therefore, the general form of a copula function with uniform marginal distributions is:

$$\begin{aligned} C(u, v) &= \Pr[U \leq u, V \leq v] \\ U &= F_x(x) \\ V &= F_y(y) \end{aligned} \quad (5)$$

where U and V are the uniform marginal distribution of X and Y variables, and C is the joint distribution function.

Copulas can provide how variables move together, up or down. This feature is the key characteristic of the Copula function that lets us figure out the structure of the tails or distribution of probability. The structure can be defined as Eqs. (6) and (7), where λ_L and λ_U refer to the top and bottom tails [40]:

$$\begin{aligned} \lambda_L &= \lim_{u \rightarrow 0} \Pr[X \leq F_x^{-1}(u) \mid Y \leq F_y^{-1}(u)] \\ &= \lim_{u \rightarrow 0} \frac{C(u, u)}{u} \end{aligned} \quad (6)$$

$$\begin{aligned} \lambda_U &= \lim_{u \rightarrow 1} \Pr[X \leq F_x^{-1}(u) \mid Y \leq F_y^{-1}(u)] \\ &= \lim_{u \rightarrow 1} \frac{1 - 2u + C(u, u)}{1 - u} \end{aligned} \quad (7)$$

About Copula functions, Elliptical and Archimedean functions are the two main categories, in which the first group has a finite form and measures the dependency of symmetric tails like N (normal distribution) and t (Student's t distribution). In the second group, Archimedean functions can produce functional form through generating functions such as C (Clayton), J (Joe), F (Frank), and G (Gumble). Moreover, other kinds of Copulas are called Vine Copulas like Regular Vine (R-Vine), Canonical Vine (C-Vine), and Drawable Vine (D-Vine) functions that can portray the structural dependence for multivariate random variables (more than two variables). Vine Copulas, through joining the different families, are powerful enough to model mutual dependencies when facing high-dimensional problems. Among all, the model based on C-Vine has been found to increase wide utilization and is the most suitable structure for a case study. C-Vine Copulas are considered most suitable for identifying the multivariate dependence structure. Equation (8) presents the general functional form of Vine Copulas, where v and C are the conditional variables and multivariate Copula function. All parameters and marginal distributions are estimated

through the maximum likelihood estimation (MLE) technique [4, 10, 20]:

$$F(x|v) = \frac{\partial C_{x,v|v-j}(F(x|v-j), F(v_j|v-j))}{\partial F(v_j|v-j)} \quad (8)$$

Data Collection

Time-series data from 1961 to 2019 for Iran have been derived. The data regarding AFOLU-related activities from the most cultivated and strategic crop yields and products are considered explanatory variables. The data are horticulture crops (in thousand tons) including Apple, Apricot, Cherries, Date, Other fruits, Citrus, Nuts, Peaches, Pears, Strawberry, and Grapes, crops yields (Thousand tons) like Legumes, Barley, Vegetable, Maize, Melons, Potato, Onion, Rice, Seeds, Sugar beet, Tea and Tobacco, Tomato, and Wheat, livestock and poultry productions (thousand tons) including Meat, Milk, and Egg. The study considers the main contributors to GHG emissions, CO₂, N₂O, and CH₄ emissions (Gigagram) from agricultural activities as dependent variables. All required data are collected from the Food and Agriculture Organization (FAO) database.¹ The empirical analyses have been conducted through STATA² and RStudio³ (with Vine Copula package⁴) software.

Results and Discussion

Unit-Root Test Results

The starting point is the stationarity analysis. The stationary properties of the variables are checked by ADF and KPSS tests. According to Table 1, except for citrus, strawberries, rice, and sugar beet, the null hypothesis of the ADF test is rejected (at least at a 5% significance level) for all variables for at least two pollutant emissions. In other words, the great majority of the variables are stationary at the first difference, or I(1). Regarding the KPSS test, the null hypothesis is rejected everywhere, and the results prove that all variables are stationary at the first differences.

Granger Causality Results

This section elaborates on the findings of the GC among AFOLU activities and GHG emissions. Table 2 shows the

¹ <https://www.fao.org/faostat/en/#data/QCL> and <https://www.fao.org/faostat/en/#data/GT>.

² <https://www.stata.com/stata17/>.

³ <https://cran.r-project.org/bin/windows/base/>.

⁴ <https://cran.r-project.org/web/packages/VineCopula/index.html>.

Table 1 ADF and KPSS stationarity tests results

Sector	Variables	ADF (Levels)	ADF (Differences)	ADF result	KPSS result	
Horticulture	Apples	- 2.19	- 6.92***	I(1)	I(1)	
	Apricots	- 1.13	- 10.06***	I(1)	I(1)	
	Cherries	- 1.37	- 9.84***	I(1)	I(1)	
	Dates	- 0.32	- 7.79***	I(1)	I(1)	
	Other fruits	- 0.61	- 11.98***	I(1)	I(1)	
	Citrus	- 3.46**	-	I(0)	I(1)	
	Nuts	- 1.51	- 12.05***	I(1)	I(1)	
	Peaches and Nectarines	- 0.40	- 9.34***	I(1)	I(1)	
	Pears	- 1.93	- 7.96***	I(1)	I(1)	
	Strawberries	- 3.41**	-	I(0)	I(1)	
	Grapes	- 2.02	- 10.40***	I(1)	I(1)	
Crop Farming	Legumes	- 1.62	- 8.28***	I(1)	I(1)	
	Barley	- 1.85	- 9.24***	I(1)	I(1)	
	Vegetables	- 1.96	- 10.911***	I(1)	I(1)	
	Maize	- 1.41	- 9.32***	I(1)	I(1)	
	Melons	- 2.09	- 8.70***	I(1)	I(1)	
	Potatoes	- 1.70	- 8.04***	I(1)	I(1)	
	Onions	- 2.07	- 9.45***	I(1)	I(1)	
	Rice	- 2.91**	-	I(0)	I(1)	
	Sugar beet	- 2.77**	-	I(0)	I(1)	
	Tea and Tobacco	- 1.69	- 8.63***	I(1)	I(1)	
	Tomatoes	- 1.48	- 8.81***	I(1)	I(1)	
	Wheat	- 1.61	- 9.91***	I(1)	I(1)	
	Livestock and Poultry	Meat	- 2.07	- 7.53***	I(1)	I(1)
		Milk	- 1.73	- 8.35***	I(1)	I(1)
		Eggs	- 2.03	- 7.76***	I(1)	I(1)
Honey		0.39	- 6.33***	I(1)	I(1)	
Pollutants	CH ₄	- 1.13	- 6.53***	I(1)	I(1)	
	N ₂ O	- 0.97	- 6.59***	I(1)	I(1)	
	CO ₂	- 1.17	- 7.22***	I(1)	I(1)	

***, **, and * represent 1%, 5%, and 10% of significance levels, respectively

results of the GC tests among crops, productions, CO₂, N₂O, and CH₄ emissions. GC results only show the direct effect of AFOLU-related activities on a change in GHG emissions and are useful for determining whether AFOLU-related activities forecast GHG emissions. Outcomes of the GC tests reveal that most of the null hypotheses are rejected. In other words, AFOLU-related activities, horticulture and farming crops, livestock and poultry production Granger cause CO₂, N₂O, and CH₄ emissions. In more detail, for horticulture crops, apples, apricots, dates, citrus, peaches and nectarines, and pears Granger cause CO₂, N₂O, and CH₄ emissions; however, strawberries and grapes Granger cause CO₂ and N₂O emissions, while cherries cause CO₂ and CH₄ emissions; other fruits cause N₂O and CH₄. It seems that horticulture crops lead to changes in environmental pollution, particularly raising CO₂

emissions. Furthermore, it is evident from the results that crop farming is mostly responsible for CH₄ emissions. Legumes, rice, sugar beet, and tomatoes cause N₂O and CH₄ emissions; vegetables and tea and tobacco cause CO₂ and CH₄ emissions, while melons cause CO₂ and N₂O emissions, and the rest of the crops Granger cause all three pollutants. In the case of livestock and poultry production, only honey does not Granger cause emissions. These findings are in line with [12], who found a long-term relationship between crop production and CO₂ emissions in Nigeria. From the perspective of the Granger results, finding details on the dependency structure among AFOLU-related activities and GHG emissions seems imperative to achieve sustainable development.

Table 2 Granger causality results

Sector	Variable	CH ₄	N ₂ O	CO ₂	
Horticulture	Apples	6.49*** (0.01)	25.69*** (0.00)	22.17*** (0.00)	
	Apricots	15.01*** (0.00)	9.92*** (0.00)	5.43** (0.02)	
	Cherries	12.51*** (0.00)	1.55 (0.21)	4.31** (0.03)	
	Dates	4.68** (0.03)	6.69*** (0.01)	9.55*** (0.00)	
	Other Fruits	12.05*** (0.01)	19.67*** (0.00)	3.09 (0.54)	
	Citrus	4.65** (0.03)	26.47*** (0.00)	59.71*** (0.00)	
	Nuts	3.56** (0.05)	1.77 (0.18)	3.48* (0.06)	
	Peaches and Nectarines	34.12*** (0.00)	13.45*** (0.00)	9.33*** (0.00)	
	Pears	24.60*** (0.00)	12.89*** (0.00)	5.65*** (0.01)	
	Strawberries	0.76 (0.38)	8.04*** (0.00)	29.78*** (0.00)	
	Grapes	2.41 (0.12)	20.43*** (0.00)	2.93* (0.08)	
Crop farming	Legumes	8.46*** (0.00)	7.09*** (0.00)	0.75 (0.38)	
	Barley	11.99*** (0.00)	11.22*** (0.00)	20.11*** (0.00)	
	Vegetables	11.29*** (0.00)	0.08 (0.77)	2.83* (0.09)	
	Maize	25.74*** (0.00)	13.63*** (0.00)	21.67*** (0.00)	
	Melons	1.70 (0.19)	6.69*** (0.01)	3.14* (0.07)	
	Potatoes	7.70*** (0.00)	13.11*** (0.00)	5.01** (0.02)	
	Onions	2.97* (0.08)	16.37*** (0.00)	15.16*** (0.00)	
	Rice	13.82*** (0.00)	10.51** (0.03)	4.81 (0.30)	
	Sugar beet	2.91* (0.08)	11.92*** (0.00)	1.28 (0.25)	
	Tea and Tobacco	3.39* (0.06)	1.13 (0.28)	7.89*** (0.00)	
	Tomatoes	10.50** (0.03)	10.18** (0.03)	6.30 (0.17)	
	Wheat	15.47*** (0.00)	14.73*** (0.00)	7.74* (0.10)	
	Livestock and poultry	Meat	8.93* (0.06)	14.40*** (0.00)	10.34** (0.03)
		Milk	9.67** (0.04)	13.89*** (0.00)	9.53** (0.04)
Eggs		8.23* (0.08)	14.22*** (0.00)	3.09 (0.54)	
Honey		4.86 (0.30)	5.60 (0.23)	6.29 (0.17)	

***, **, and * represent 1%, 5%, and 10% of significance levels, respectively

Correlation Results

From causality analysis, it emerges that changes in pollutant emissions come directly from AFOLU activities. For more details on how variables are connected to each other, we use C-Vine Copula families to measure the correlation. According to the results in Table 3, Kendall's τ parameter, the size of correlation among crop productions, CO₂, N₂O, and CH₄ emissions in the first tree and the Family column are about the Copula family that can simulate the dependency structure. We chose the first tree because of the greatest influence on model fit, while the rest trees are not applicable for analysis.

Based on the results, the highest correlation was found between rice cultivation and CH₄ emissions ($\tau = 0.37$). The dependency of symmetric tails is measured through the Archimedean Frank Copula. The correlation highlights the strong relationship between rice cultivation and environmental degradation, which implies that as rice cultivation

increases, methane emissions change in the same direction. Because rice is one of the most abundant crops grown and consumed in Iran, as a result, it generates more methane emissions. These findings are in line with [11, 15, 32, 40], who highlighted that rice farming is one of the top sources of GHG, especially methane emissions. However, a contrast emerges with [41], who confirmed that rice farming is responsible for 80% of local CO₂ emissions, but it is not always consistent because of the weak decoupling. This difference could be attributable to the methods employed, variations in climate, or the difference in terms of the dependent variable.

For crop and livestock productions, vegetables, meat, milk, wheat, and barley are the other variables that exhibit a significant positive correlation with methane emissions. (τ is equal to 0.33, 0.31, 0.31, 0.24, and 0.23, respectively.) The dependencies are simulated through the Frank and Survival Joe Copula families. These relationships show that as crop and livestock products increase, methane

Table 3 Correlation analysis

Sector	Variables	CH ₄		N ₂ O		CO ₂	
		Family	τ	Family	T	Family	τ
Horticulture	Apples	SJ	0.08	N	0.06	BB8	0.22
	Apricots	SJ	0	C90	0	SJ	0.16
	Cherries	SJ	0.17	SG	0.15	N	- 0.07
	Dates	N	- 0.06	F	0.05	BB8_90	- 0.19
	Other fruits	SJ	0	C270	0	N	- 0.13
	Citrus	SJ	0.18	SJ	0.10	F	0.12
	Nuts	SG	0.17	N	0.11	N	0.04
	Peaches and Nectarines	SJ	0.09	BB8_270	- 0.13	N	- 0.07
	Pears	BB8_270	- 0.12	F	- 0.11	N	0.04
	Strawberries	-		SJ	0.10	F	0.12
	Grapes	-		F	- 0.12	F	- 0.05
Crop farming	Legumes	SJ	0.09	F	0.21		
	Barley	SJ	0.23	C	0.11	F	- 0.03
	Vegetables	F	0.33	-		J	0.10
	Maize	N	0.16	BB8	0.20	F	- 0.11
	Melons	-		F	0.17	J	0.1
	Potatoes	C90	- 0.01	F	0.14	F	0.18
	Onions	C	0.13	C	0.09	J	0.10
	Rice	F	0.37	C	0.19	N	- 0.05
	Sugar beet	F	- 0.02	F	0.12	-	
	Tea and Tobacco	C	0.19	-		SC	0.01
	Tomatoes	C	0.17	F	0.13	-	
Wheat	SJ	0.24	SJ	0.14	F	- 0.1	
Livestock and poultry	Meat	SJ	0.31	C	0.18	t	0.03
	Milk	SJ	0.31	C	0.19	N	0.02
	Eggs	C	0.25	F	0.2	F	0.08

Best-fit copula for each edge, where N-Normal Copula, F-Frank Copula, C-Clayton Copula, SG-Rotated Gumbel Copula (180 degrees, “survival Gumbel”), and SJ-Rotated Joe Copula (180 degrees, “survival Joe”), BB8_270-Joe-Frank Copula, C90-Rotated Clayton Copula (90 degrees)

emissions change in the same direction. It seems that fuel, inorganic fertilizers, and pesticides used in crop farming emit CH₄ emissions that can negatively contribute to climate change. In the case of livestock products in Iran, sheep are the most numerous, followed by cows; so, the rising demand for animal products pushed up both animal husbandry and CH₄ emissions. These findings are in line with [3, 15, 31, 37], who found that livestock production is the main source of CH₄. Contrarily, the lowest correlation is measured and simulated between pears and dates crops and methane emissions with values of - 0.12 and - 0.05, respectively, for Kendall's τ , by using Normal and Joe-Frank Copulas. This shows that as pears and dates crops increase, methane emissions move in the opposite direction, improving the environment. A plausible explanation may be that trees represent a net source or sink of methane emissions depending on the season and their age. Apple, cherry, citrus, nuts, peach and nectarine, legume, maize, onion, tea and tobacco, and tomato productions are weakly

but positively correlated with methane emissions. Meaning that these crops negatively contribute to climate change and sustainable development. In addition, no relationship is established between methane emissions and apricots, other fruits, strawberries, grapes, and melons.

In the case of N₂O emissions, a statistically significant relationship is found among legumes, maize, eggs, rice, and N₂O emissions with values for τ of 0.21, 0.20, 0.20, and 0.19, respectively. The high positive correlation proves that N₂O emissions increase along with production increases. The reason could be due to the application of synthetic and inorganic fertilizers, cropping practices, manure management, and burning crop residuals. Meat, milk, melons, and cherries are also correlated with emissions with τ values of 0.18, 0.19, 0.17, and 0.15, respectively. The correlations are simulated by using Clayton, Frank, and Survival Gumbel families. This correlation can be explained through the livestock feed production process, which often involves large applications of nitrogen-based

Table 4 Summary of the main results

Sector	Effects	CH ₄	N ₂ O	CO ₂
Horticulture	Increase	Citrus, Nuts, Cherries	Cherries, Citrus, Strawberries	Apples, Apricots
	Decrease	Pears, Dates	Pears, Grapes	Dates, Other fruits
Crop farming	Increase	Rice, Vegetables	Legumes, Maize, Rice	Potatoes, Onions, Vegetables
	Decrease	Sugar beet, Potatoes	–	Wheat, Barley
Livestock and Poultry	Increase	Meat, Milk	Eggs	Eggs
	Decrease	–	–	–

fertilizer to soils. This in turn results in nitrification and denitrification in the soil and the release of nitrous oxide into the atmosphere. In the opposite direction, peaches and nectarines, grapes, and also pears are environmentally friendly. The dependency structure is constructed through Joe–Frank and Frank Copula families with τ values of -0.13 and -0.12 , respectively. A reason similar to methane emissions can be invoked: trees can be a net source or sink of N₂O emissions. Furthermore, we found that apricots and other fruits are not related to N₂O emissions. In this case, our results support those of [31], who showed that AFOLU activities, particularly livestock production and crop farming, are responsible for CH₄ and N₂O emissions.

Regarding CO₂ emissions, potato and apple crops have the greatest relationship with this kind of emissions. Frank and Joe–Frank Copulas measured the dependencies of symmetric tails. The high positive correlations, 0.18 and 0.22 for τ , implied significant relationships between them, in which emissions increases follow production increases. This should be linked to diesel fuels and non-renewable electricity consumption for agricultural operations, fertilizers, and pesticides. Most of the horticulture crops are negatively correlated with emissions, i.e., dates, other fruit, cherry, peach and nectarine, and grape productions, with values of -0.19 , -0.13 , -0.07 , -0.07 , and -0.05 , respectively, are environmentally friendly. The simulated structure can be explained through Joe–Frank, Normal, and Frank families. The weak but negative correlations implied inverse relationships, in which the emissions decrease is combined with production increases. The possible reason is that most of the trees absorb more than 48 pounds of CO₂ in a year. The rest of the crops and products (apricots, citrus, nuts, pears, strawberries, vegetables, melons, onions, meat, milk, and eggs) show a moderate positive correlation with CO₂ emissions. The correlation ranges from 0.02 to 0.16, and is simulated by using the Archimedean functions. These relationships exhibit that, as crop and livestock products increase, CO₂ emissions change in the same direction. A possible reason could be the use of

non-renewable energy for those activities. In this regard, similar results are reported by [2, 22, 38].

As a result, most of the farming crops and livestock productions show a high positive correlation with CH₄ and N₂O emissions. However, we found a moderate correlation between horticulture crops and CH₄ emissions. In addition, these crops show significant negative impacts on CO₂ emissions. For more detail, citrus, nuts, cherry, rice, vegetable, meat, and milk production are the activities that intensify methane emissions; on the contrary, pears, dates, sugar beet, and potatoes can relatively smooth the emissions. At the same time, cherries, citrus, strawberries, legumes, rice, and maize enhance N₂O emissions, but pears and dates reduce the emissions. Wheat and barley farming, unlike apple, apricot, potato, onion, vegetable, and egg production, are able to protect the environment (see Table 4). It seems that most of the AFOLU-related activities from farming crops and livestock productions in the Iranian agriculture sector release a significant amount of CH₄ emissions, followed by N₂O emissions. Despite this, horticulture crops are mostly responsible for mitigating CO₂ emissions.

Conclusions

The study aims to analyze the correlation and causality nexus between agricultural activities and different pollutants responsible for GHG emissions in Iran. To this extent, several agricultural products are categorized into three main groups: horticulture and farming crops, livestock, and poultry production. The data are collected from the FAO database over the period 1961–2019. GC test is used to examine the causality relationship between variables, while C-Vine Copula families are applied to measure the correlation.

According to the causality results, most of the crops Granger cause the emissions. In terms of correlation, most farming and livestock products are responsible for CH₄ emissions, followed by N₂O emissions. However, most horticulture crops are environmentally friendly. Among all,

rice, vegetables, meat, and milk products show a significant correlation with CH₄ emissions. The emissions increase due to an increase in those productions. In fact, rice and vegetable cultivations, increasing the blocks of oxygen from penetrating soil in the water and creating ideal conditions for methane-emitting bacteria, are significant activities that may increase emissions. Livestock production, including different kinds of meat and milk from sheep and cows, shows a considerable correlation with methane emissions due to an increase in enteric fermentation. The same conclusion is found in the case of the UK [3], China [15, 36, 40], India [31], Malaysia [11], and Bangladesh [37]. Therefore, Iranian livestock and crop products are mainly responsible for CH₄ emissions and need further investigations on how sustainable policies can change/smooth the dependency direction, for example, how China [41] could smooth the emissions through new farming technologies.

Legumes, maize, rice, milk, and meat are the main drivers of N₂O emissions, because of the high nitrate–N-fertilizers consumption in the cropping process and the use of nitrate in animal feed, which has increased since 1990 in developing countries, particularly in the Iranian agriculture activities. Our findings match the analysis in [31] on the effects of AFOLU activities on GHG, especially N₂O emissions. Apples are the main factor of CO₂ emissions, as apple orchards are one of the net C (carbon) sinks and one of the important production systems in the horticulture sector. It is noteworthy to mention that CO₂ emissions decrease significantly due to increased horticulture production. This implies that most horticulture activities are a helpful way to achieve sustainable goals. In the same vein, [12, 38] provided similar outcomes.

Based on these empirical findings, we can recommend useful policy implications. Horticulture activities, particularly pear, date, peach, and nectarine crops, along with preventing submergence of rice and vegetable fields, optimizing and balancing feed digestibility for the animal through new feed programs for animals, and enhancing animal health can smooth CH₄ and N₂O emissions. In addition, to limit N₂O emissions the use of inorganic N-fertilizers in crop production could represent another sustainable policy recommendation. To reduce CO₂ emissions, energy sources should transfer from fossil to renewable, for example, water pumps ought to be converted from gasoline to solar energy sources, and horticulture activities, especially fruit, date, grape, peach, and nectarine crops should be expanded along with them.

Future research may inspect the same topic by implementing different and innovative empirical methodologies (Machine Learning or Artificial Neural Network experiments, Wavelet Analysis) [26].

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Declarations

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