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Metadata Analysis to Evaluate Environmental Impacts of Wheat Residues Burning on Soil Quality in Developing and Developed Countries

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Abstract: Crop residues are widely considered as a biofuel source and used in livestock feeding, or are burned off to clean the field for tillage and planting. Nonetheless, crop residue burning poses serious threats to the soil stability and sustainability of the food chain. This study aimed to investigate the potential environmental impacts of wheat residues burning on declines in soil quality in developing (Iran) and developed (Italy) countries by analyzing metadata of the last 50 years. All metadata were provided from the 'Food and Agriculture Organization of the United Nations' (FAO) including wheat harvested area, annual production, and biomass burning, to assess the potential impact of crop residue burning on soil quality. In detail, the greenhouse gases (GHGs) emission, and energy and nutrient losses by the wheat residues burning were estimated. Our results showed a robust interdependence between wheat residues burning and environmental effects in both developed and developing systems. Accordingly, the global warming potential increased in Iran (4286 to 5604 kg CO_2eq) and decreased in Italy (3528 to 1524 kg CO_2eq) over the last 50 years. Amongst all nutrient losses, nitrogen represents the higher lost value in both countries, followed by potassium, sulfur, and phosphorus.

Keywords: agroecosystem sustainability; climate change; crop residue burning; food security; soil quality

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1. Introduction

Agriculture is vital for achieving food security as the main sustainable development aim of the world. Declining the availability of arable land, decreasing agricultural production by negative impacts of climate change and increasing global population will lead to serious world challenges in the future decades [1]. Therefore, to overcome these challenges and to produce food for the growing global population, highly resource-efficient practices will be needed to reach higher productivity along with fewer inputs such as water, chemical inputs (i.e., fertilizers and pesticides), and fossil energy [2], and consequently reduced costs of environmental effects [3].

Crop residue management is one of the main practices to achieve soil health and sustainability for increasing crop yield and overcoming food security and climate change challenges [4]. Farmers usually add their crop residues to the soil for providing organic nitrogen and carbon source for nitrification and microbial mineralization and growth [5]. Also, suitable crop residue management reduces soil erosion by water and wind [6], increases water holding capacity on the topsoil layers [7], and improves soil conditions for earthworms activity [8]. Crop residues can also be considered as a potential source of biofuel as renewable energy and feeds for livestock [8]. Alternatively, crop residue burning is a convenient method for farmers to deplete and clean their fields rapidly [9,10]. When crop residues are burned, all of the above-mentioned benefits will be lost, and other adverse impacts on the environment may appear.

Previous studies showed that crop residue retention in the field positively enhances soil quality and crop productivity [11,12]. Liu et al. [13] did a meta-analysis and reported that straw carbon input increases crop yield up to 12.3% in agriculture systems. Crop residue retention also increased the recovery of fertilizer-derived nitrogen (N) in vegetative biomass by 110% and fertilizer N recovery by 41% in the soil-crop system [12]. Smallholders frequently burn crop residue because they believe that such practice has a beneficial influence on crop growth and yield [14]. According to several literature searches on crop residue burning, burning crop residues may have positive short-run effects while many negative long-run effects on soil and environmental health are reported. The increasing availability of minerals such as phosphorus and potassium and/or improving crop productivity in the subsequent growing season were defined as positive short-run effects [15]. In contrast, the loss of crop nutrients up to 80% for N, 100% for carbon (C), 20% for phosphorus (P), 50% for sulphur (S), and 25% for potassium (K), changes in soil microbial population, and effect on public health and environment, were considered as negative long-run ones [16,17].

On the other hand, avoiding crop residue burning and its incorporation can increase soil nutrient content, nitrogen uptake, potential nutrient recycling, and microbial composition and activity, contributing to higher crop productivity [14,18–23]. For example, crop residue burning decreases rice yield by 46% as compared to residue incorporation [24]; in other studies, wheat yield declined by 20.3% in comparison with the surface retention of crop residues [25], while El-Sobky [26] reported also that rice straw burning results in N losses as well as several elements such as K, P, S, Calcium (Ca), and Magnesium (Mg).

In addition to fossil fuels, crop residues burning is a main air pollution source on a regional as well a global scale [27]. The burning of crop residues leads to the emission of air pollutants such as particulate matter (PM_{10}, $PM_{2.5}$, PM_1), trace gases, volatile organic compounds (VOCs), along with greenhouse gases (GHGs) [28]. Unlike other air pollution sources, GHGs emission by crop residues burning occurs for large volumes within a short period. Previous studies in different countries documented well that crop residues burning has a negative effect on air quality and public health [29–32].

All the above considered, the current study aimed to investigate the impacts of wheat residues burning on agri-environmental soil quality by analyzing metadata of the last 50 years reported by FAO and calculating the GHG emission, energy, carbon, and nutrient losses. In this study, we focused on Iran and Italy, representative of two developing and developed countries, which have had completely different trends according to the FAO data in terms of wheat residues burning, wheat harvested area, and annual production during the studied period. In 2019, Iran and Italy were ranked the 11th and 22nd countries among the largest wheat producers, with a production of 16.8 and 6.7 million tons of grain, respectively [33].

2. Materials and Methods

2.1. Site Description

Iran is located between 44° and 64° E longitude and 24° and 40° N latitudes. Iran has an area of 1.648 million km^2 with ~16.5 million ha of agricultural land. The climate is hot and dry, with extremely hot and long summers and cool and short winters. Based on the Köppen method, the climate of Iran is divided into four zones namely arid desert, semiarid, humid with mild winters, and humid with severe winters. The mean annual rainfall is about 250 mm, which occurrs up to 50 mm in the desert and 1600 mm in Caspian

Sea coastal area. January (5–10 °C) and August (17–34 °C) were the coldest and hottest months in Iran, respectively. The trends of cultivated area, wheat production, and grain yield during the past five decades are shown in Figure 1, and reflect that wheat area cultivation, grain production, and grain yield increased by 30, 171, and 254% from 1968 to 2018, respectively [33].

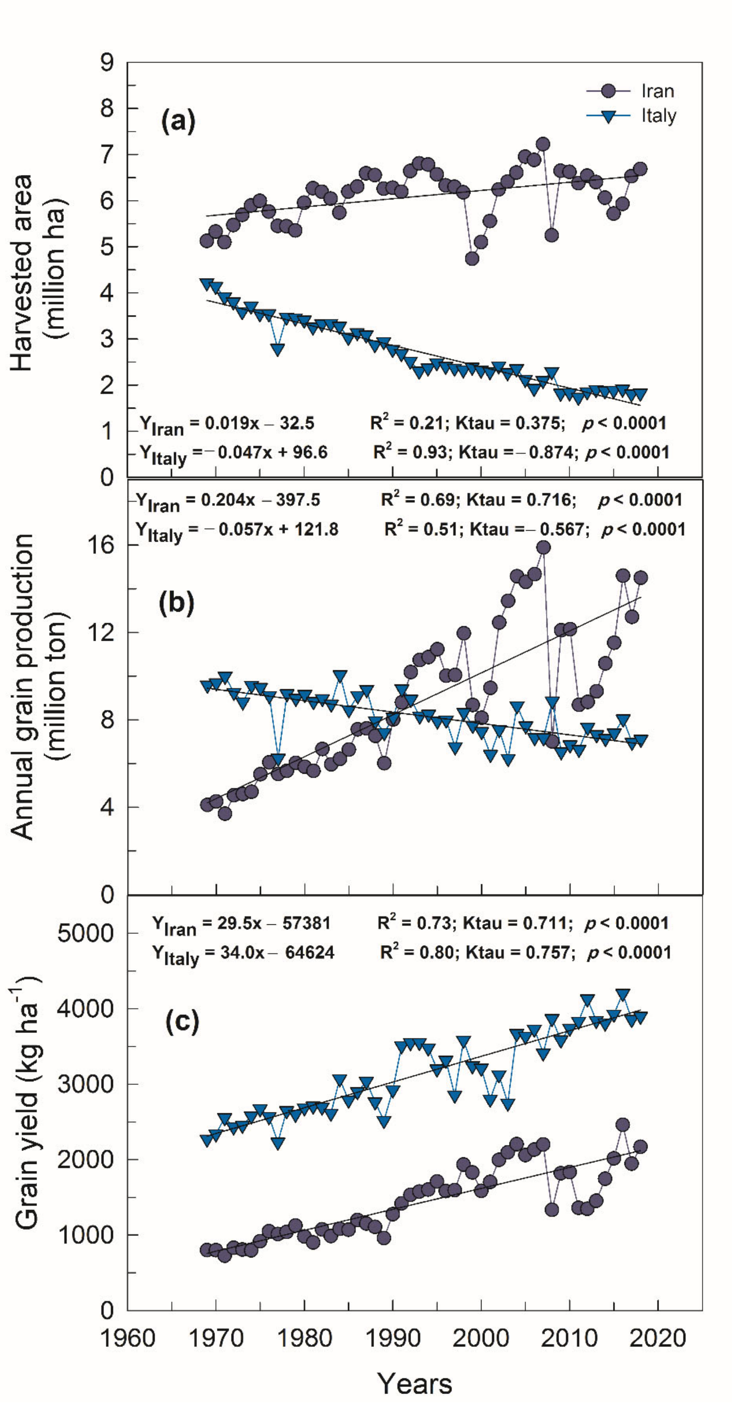


Figure 1. Trends of wheat harvested area (**a**), annual grain production (**b**), and grain yield (**c**) in Iran and Italy during 1969–2018. R^2, Ktau and $p < 0.0001$ are the coefficient of determination, Kendall's tau value, and significant at 0.0001 probability level, respectively.

Italy is located between 6° and 19° E longitude and 35° and 47° N latitudes, with an area of 0.3 million km^2 with ~12.7 million ha of agricultural land. Italy has hot and dry summers and cool and wet winters, and is classified as a Mediterranean climate. Mean annual rainfall varies from about 500 mm on the southeast coast and in Sicily and Sardinia, to over 1200 mm in the north. The coldest and hottest months in Italy are January and August with an average of 8 and 25 °C, respectively. In Figure 1, the trends of harvested area, wheat production, and grain yield during the past five decades are presented. Wheat area cultivation and grain production decreased by 135 and 36% from 1968 to 2018, respectively, while grain yield increased by 73% in 2018 as compared to 1968 [33]. Soils are mainly classified as Cambisols and Anthrosols in Italy, and Fluvisols, Leptosols and Regosols in Iran based on the world reference base (WRB) classification [34].

2.2. Data Collection and Analysis Method

The data used in this study, including wheat harvested area, grain production, grain yield, and residue biomass burning (Figures 1 and 2) were collected from the FAO website (http://www.fao.org/faostat/en/#data/GB (accessed on 22/12/2020)). Data were from 1969 to 2018 for both Iran and Italy as examples of developing and developed countries, respectively. These data are annually submitted to FAO by national correspondents of ministries or institutions and are free access for all users through the FAO website at http://www.fao.org (accessed on 22/12/2020).

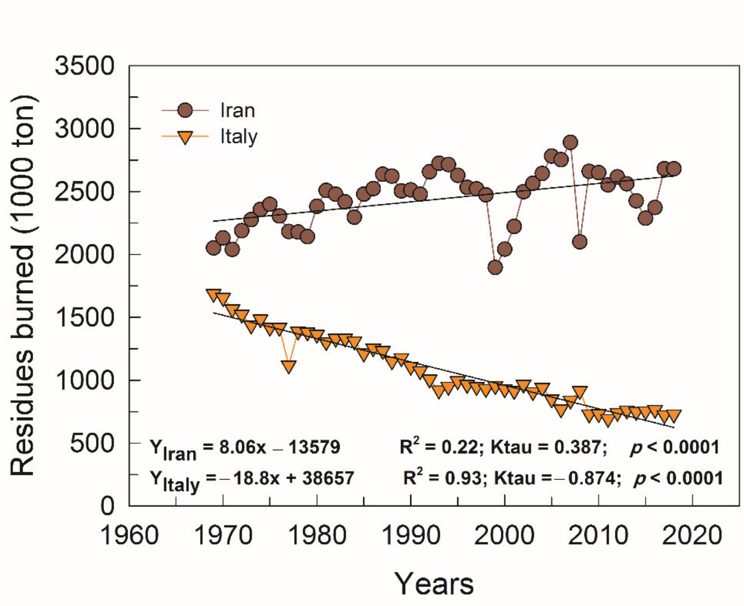


Figure 2. Wheat residues burning in Iran and Italy during 1969–2018. R^2, Ktau, and $p < 0.0001$ are the coefficient of determination, Kendall's tau value, and significant at 0.0001 probability level, respectively.

The GHG emission, energy, carbon, and nutrient losses by wheat residues burning were calculated. Crop residue burning may emit a remarkable quantity of the main air pollutants such as CO_2, N_2O, and CH_4. The comprehensive emission record for these three air pollutants (i.e., CO_2, N_2O, and CH_4) was prepared using IPCC, 2019 Refinement to the 2006 IPCC guidelines [35] for the studied years (i.e., 1969–2018). The emission coefficients per kg wheat residue burned were 1787, 0.74, and 3.55 g for CO_2, N_2O, and CH_4, respectively.

The estimation of GHGs as CO_2 equivalent emissions (CO_2eq) was calculated using Equation (1) [36].

$$\text{Greenhouse effect} = \sum \text{GWPi} \times \text{mi} \quad (1)$$

GWPi is the global warming potential for CO_2, CH_4, and N_2O (1, 21, and 310, respectively), and mi is the mass (kg) of the emission gas. The score is expressed in terms of CO_2 equivalents.

Farmers burn wheat residue (i.e., straw) in a field during the harvest season, thus energy losses based on straw energy coefficient was estimated in this study. The straw energy coefficient was assumed as 12.5 GJ ton^{-1} [36].

During residues burning, the larger parts of carbon, nitrogen, and sulphur were lost to the atmosphere as gases, but other nutrients such as P, K, Ca, and Mg were mostly returned to the soil as ash residues [37]. The concentrations of N, P, K, and S in wheat straw were reported to be 0.51, 0.05, 1.28, and 0.13%, respectively [38]. Also, the amounts of these nutrients lost during wheat residues burning were 85, 10, 11, and 65% of total existing nutrients in wheat straw [16].

"The authors declare that all presented data in the current research have been re-deposited on Zenodo open data repository (CERN) (https://zenodo.org/ (accessed on 30/05/2021)) including its digital object identifier, http://doi.org/10.5281/zenodo.4860131 (accessed on 30/05/2021)".

2.3. Statistical Analysis

Data analysis was performed using the Statistical Analysis System ver. 9.4, Excel ver. 2013 and Sigma Plot ver. 11 software (www.systatsoftware.com (accessed on 23/08/2008)). The Mann-Kendall test was used to estimate whether the time series has a monotonic upward or downward trend.

3. Results and Discussion

Crop residue management is one of the main strategies to overcome food insecurity and climate change challenges with the main target to increase crop yield and carbon sequestration by rational soil use and management. In the present study, the potential environmental impacts of wheat residues burning on energy and nutrient losses in developing (Iran) and developed (Italy) countries were investigated by analyzing metadata of the last 50 years reported by FAO.

According to the FAO data, there was a significant difference between Iran and Italy in terms of the wheat harvested area during the studied period (Figure 1a). Indeed, the differences between these countries increased with time, from 1.2-fold in 1969 to 3.7-fold in 2018 (Figure 1a). In Iran, the harvested area was ~5.12 million ha in 1969, then increased linearly at the rate of 0.019 million ha per year, reaching ~6.68 million ha in 2018 (23.3% increase than its initial value), whereas in Italy, the harvested area decreased significantly from 4.22 million ha in 1969 to 1.82 million ha in 2018, indicating a 2.3-fold decrease in the harvested area during the past 50 years. In detail, the rate of decrease was 0.047 million ha per year for Italy (Figure 1a). The fluctuation of the harvesting area in Iran was more than that observed in Italy, which was due to severe temperature fluctuations and water deficit in some years in Iran, reflecting a sharp decline in the harvested area.

The wheat annual production varied in both countries (Figure 1b). On the other hand, in 1969, wheat production was 2.3-fold higher in Italy as compared to Iran, then linearly decreased (0.057 million ton per year, as line slope), reaching 7.1 million ton, showing an overall 25.9% decrease during the past 50 years (Figure 1b). In contrast, wheat production remarkably increased with time in Iran (from 4.2 to 14.5 million ton), with a rate of 0.204 million ton per year (Figure 1b). Besides, during 1990–1992, the production was the same for both countries (9.0–9.5 million ton).

Figure 1c depicts the trends of wheat grain yield per ha for both countries in the last fifty years. On average, the grain yield was significantly higher in Italy (~50%) than that found in Iran, for all of the studied years. However, the same pattern was estimated in both countries, which means that the grain yield enhanced linearly with time (from1969 to 2018), from 2272 to 3900 kg ha^{-1} in Italy and from 800 to 2169 kg ha^{-1} in Iran, respectively, suggesting that wheat grain yield was promoted by technology adoption and also by using high-yielding wheat genotypes in recent decades. The rate of increase was 34.0 and 29.5 kg ha^{-1} year^{-1} in Italy and Iran in this period, respectively (Figure 1c). Such increase, higher in Italy, is very likely due to a massive application of advanced technologies in a developed country, clearly indicating that technology is an essential factor to decrease the yield gap in crop production [39].

3.1. GHG Emission

Based on data reported by FAO, the annual residue burning decreased remarkably with time from 1969 to 2018 in Italy (1687 vs. 728 thousand tons CO_2eq, decreasing by 18.8 thousand tons CO_2eq per year), while in Iran this value slightly increased with time (2050 vs. 2680 thousand tons, increasing by 8.06 thousand tons CO_2eq per year), which was directly related to the harvested area in both countries (Figure 2). The wheat residues burning increased by 30.73% in Iran and declined by 56.81% in Italy during the studied period (Figure 2).

Figure 3 reports the GHGs emissions (i.e., CO_2, N_2O, CH_4, and GWP) by wheat residues burning yearly from 1969 to 2018, in both countries. The results indicate that all GHGs emissions increased linearly with time in Iran while the inverse pattern was found in Italy. These changes in the GHGs emissions were mainly due to the changes in the wheat harvested area and production in both countries. As shown in Figure 1b, wheat production increased by 253% in Iran and decreased by 26% in Italy from 1969 to 2018 (Figure 1b). According to the Mann-Kendall test, from 1969 to 2018, the increase rates of CO_2, N_2O, CH_4, and GWP were 14.4, 1.85, 0.60, and 16.8 thousand tons per year in Iran and their decrease rates were 33.6, 4.32, 1.41, and 39.4 thousand tons, CO_2eq per year in Italy, respectively (Figure 3). Also, the amount of GHGs emissions was remarkably higher in Iran as compared to Italy across all the studied years. Amongst all GHGs, CO_2 shows a higher value than N_2O and CH_4 in both countries. In general, the calculated GWP was 4701-, 4869-, 5037-, 5205-, 5373-, and 5507-thousand tons CO_2eq for Iran and 3213-, 2819-, 2425-, 2031-, 1637-, and 1322-thousand tons CO_2eq for Italy in the years 1970, 1980, 1990, 2000, 2010, and 2018, respectively, remarking a significant difference between the two countries (Figure 3b). According to the Mann-Kendall test, the energy losses increased by 16.8 thousand tons CO_2eq per year in Iran and decreased by 39.4 million thousand tons CO_2eq per year in Italy over the past 50 years.

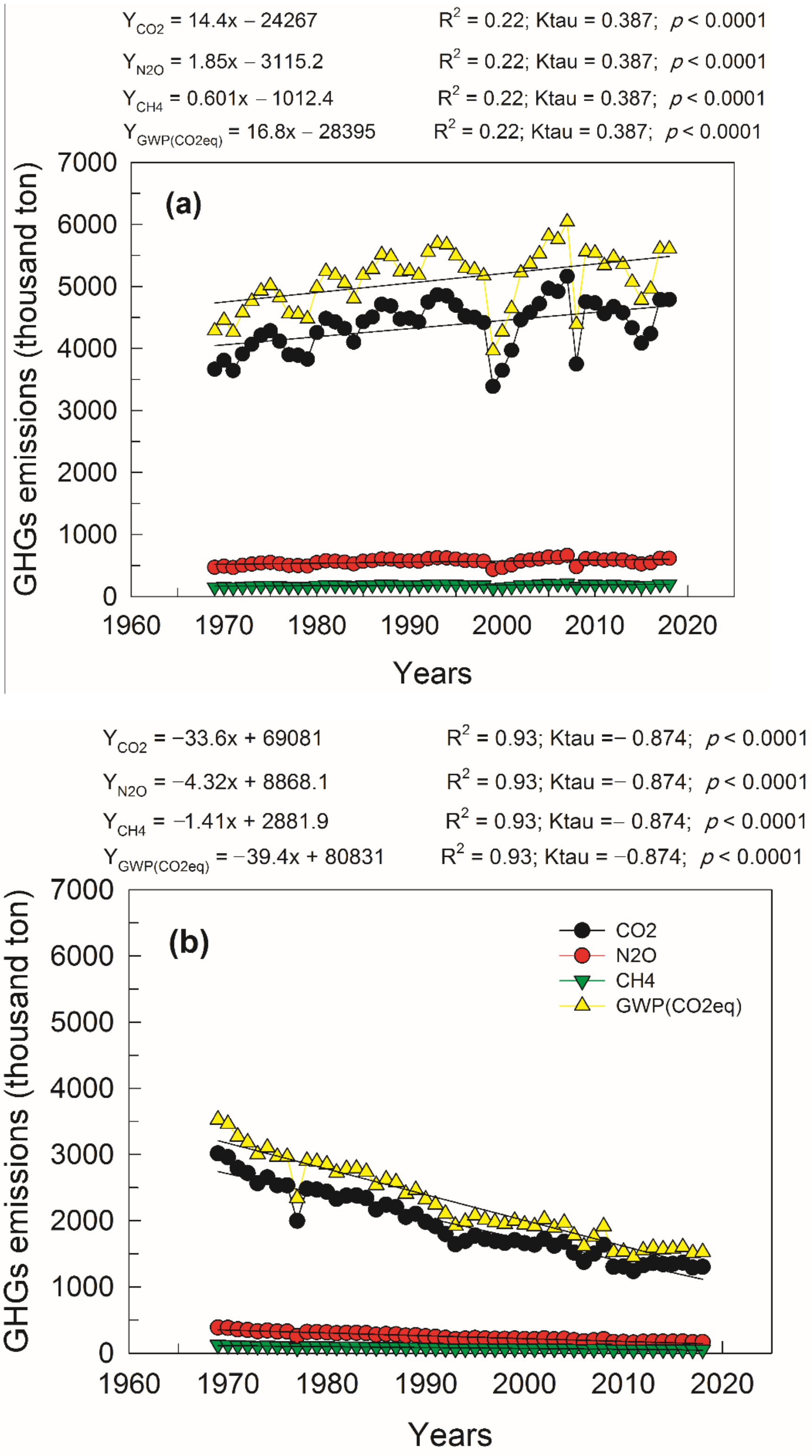


Figure 3. GHGs emission by wheat residues burning in Iran (**a**) and Italy (**b**) during 1969–2018. R^2, Ktau and $p < 0.0001$ are the coefficient of determination, Kendall's tau value, and significant at 0.0001 probability level, respectively.

Agricultural residues burning is a universal phenomenon and can be the main contributor to reduced air quality on a global scale [40]. Numerous studies have calculated the GHGs emissions from agricultural residues burning by IPCC factors in diverse species, but they reported a few air pollution factors such as CH_4, N_2O, NOx, and SO_2 [41,42]. Sun et al. [43] suggested that GHG emissions from crop residue burning should be declined by policy rules and by commercializing energy production using biomass. Some of the main challenges in crop residue management are collection, transportation, and storage space for further use (i.e., feedstock). Most of the wheat-growers in developing countries hold small lands and require to quickly clean them for the cultivation of the next crop [44], so the wheat straw is widely spread and smallholders do not have time and large storage space to pre-process residues during harvest and next sowing season [45].

3.2. Energy Losses

Crop residues burning is a common practice worldwide especially during the harvesting season [46]. It can be used as an alternative to fossil fuel and plays a key role as a source of renewable energy [47]. Generally, agricultural residues are the third greatest natural source of energy and could be consumed in the place of production by individual consumers as the main fuel, depending on several factors such as economic, social, ecological, and available technologies [47]. Several research studies all over the world reported that agricultural biomass has great potential to use as a low-carbon source for renewable energy [48–50].

Based on the FAO data, however, a large amount of wheat residue is burnt in both countries, reflecting a high amount of energy losses (Figure 2). There was a significant difference between the two countries and these differences increased with time. In Iran, the total amount of energy losses by wheat residues burning increased from 25.6 million GJ in 1969 to 33.5 million GJ in 2018, showing a 30.7% increase during this period (Figure 4). Whereas, in Italy, this value declined because of decreasing wheat harvesting area (Figures 1 and 4). The total energy losses via the wheat biomass burning ranged from 8.66 to 21.1 million GJ in Italy, depending on the year, indicating the energy losses declined by 56.8% during the studied period (Figure 4). According to the Mann-Kendall test, the historic energy losses increased by 0.10 million GJ per year in Iran and decreased by 0.24 million GJ per year over the past 50 years (1969–2018) (Figure 4).

In a study by Jiang et al. [51], the mean national density of energy potential by crop residues in Ukraine was equal to 13.45 PJ per million ha^{-1} $year^{-1}$. Jiang et al. [52] demonstrated also that the total bioenergy potential from residues in China reached 7.4 EJ in 2009. In India, Hiloidhari et al. [53] found that the estimated mean annual bioenergy potential from the crop residues biomass was 4.15 EJ, corresponding to the 17% of total energy consumption in this country.

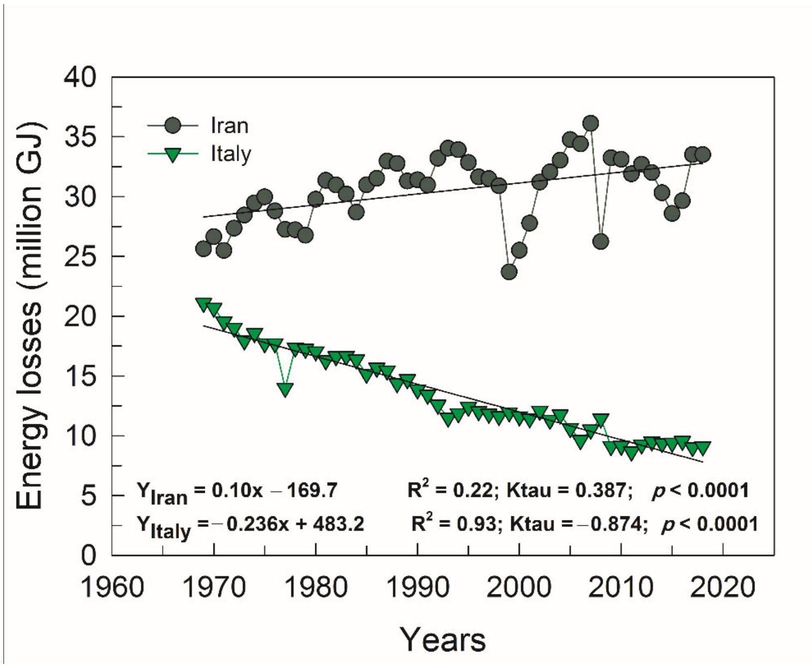
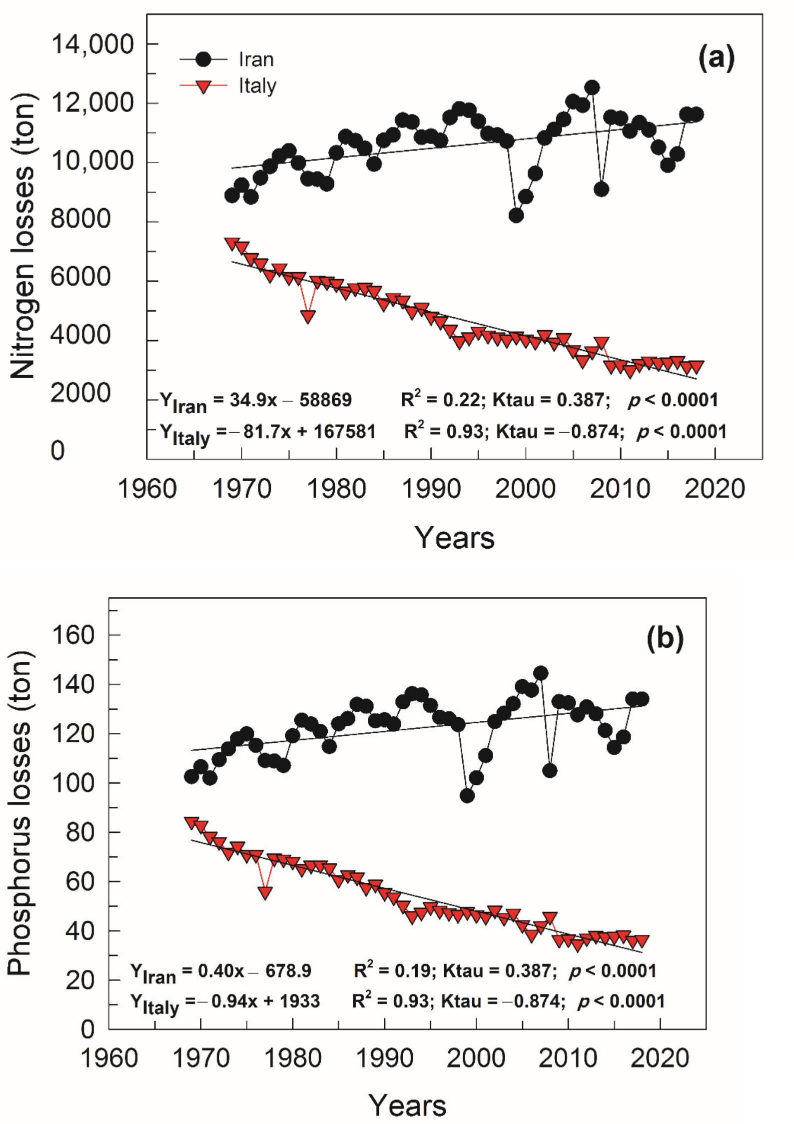


Figure 4. Energy losses by wheat residues burning in Iran and Italy during 1969–2018. R^2, Ktau and $p < 0.0001$ are the coefficient of determination, Kendall's tau value, and significant at 0.0001 probability level, respectively.

3.3. Nutrients' Losses

Soil nutrients have a vital role in plant health and growth. Three nutrients are usually addressed each year by farmers as macronutrients (i.e., N, P, and K). High yields in crops require a sufficient supply of these three nutrients during the growing season [54]. In Iran, the total N losses via wheat residues burning was 8877 tons in 1969, then increased to 11,618 tons in 2018 with a rate of 34.9 tons per year (Figure 5a). These values were 7314 and 3159 tons in the same years in Italy, respectively, reflecting a decrease (by 81.7 tons per year) in the total N losses in this country, due to decreasing of harvested area with time. On the other hand, wheat production increased from 4.1 to 14.5 million tons in Iran and decreased from 9.58 to 7.1 million tons in Italy over the past five decades (Figure 1a). Gupta et al. [20] reported that burning of crop residues raises the temperature in the topsoil up to 33.8–42.2 °C, which can decrease soil biological community on the topsoil layer (i.e., 2.5 cm) and N loss by 27–73% [55]. In a study by Singh et al. [56], the amount of N, P, K, and S losses due to burning of rice stubble in Punjab in 2001–2002 was 35, 3.2, 21, and 2.7 kg per ha, respectively.

Similar patterns were found in the P losses during the same period, that is the loss of this element increased from 102.5 to 134.0 tons in Iran and decreased from 84.3 to 36.4 tons in Italy (Figure 5b). Phosphorus lost by burning increased in Iran by a rate of 0.40 tons per year, while in Italy this value decreased by a rate of 0.94 tons per year in the studied period (Figure 5b). The amount of K losses by burning in Iran was 2886.4 tons in 1969 and then enhanced to 3773.4 tons in 2018 with a rate of 11.3 tons per year. In contrast, in Italy, its value decreased from 2375.53 to 1026 tons, respectively, with a rate of 26.5 tons per year (Figure 5c).


14,000
12,000
10,000
8000
6000
4000
2000
0
Nitrogen losses (ton)
Iran
Italy
(a)
Y_Iran = 34.9x – 58869 R² = 0.22; Ktau = 0.387; p < 0.0001
Y_Italy = –81.7x + 167581 R² = 0.93; Ktau = –0.874; p < 0.0001
1960
1970
1980
1990
2000
2010
2020
Years
160
140
120
100
80
60
40
20
0
Phosphorus losses (ton)
(b)
Y_Iran = 0.40x – 678.9 R² = 0.19; Ktau = 0.387; p < 0.0001
Y_Italy = –0.94x + 1933 R² = 0.93; Ktau = –0.874; p < 0.0001
1960
1970
1980
1990
2000
2010
2020
Years

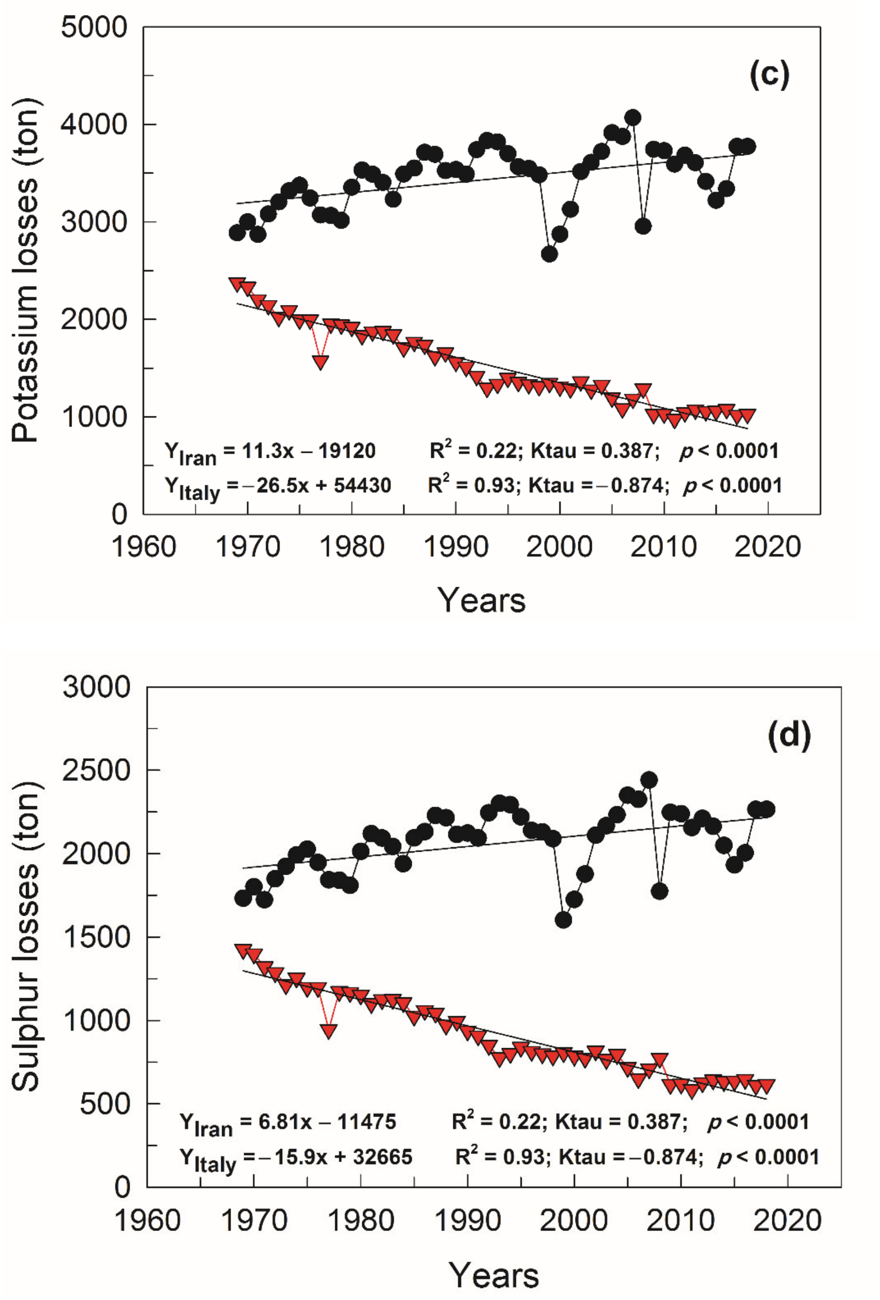


Figure 5. Nutrient losses by wheat residues burning in Iran and Italy during 1969–2018. The panels (**a**–**d**) are for N, P, K, and S elements, respectively. R^2, Ktau, and $p < 0.0001$ are the coefficient of determination, Kendall's tau value, and significant at 0.0001 probability level, respectively.

The S loss through wheat burning is shown in Figure 5d. Comparatively, the amount of S lost was significantly higher in Iran than in Italy. Indeed, the loss of S nutrient by burning wheat residues increased from 1732.2 to 2264.6 ton in Iran (30.7% higher than the initial value) and decreased from 1425.6 to 615.7 ton in Italy (56.8% lower than the initial value) when 1969 and 2018 were compared. The rate of increase in S losses with time was 6.81 ton per year in Iran, while it decreased by 15.9 ton per year in Italy (Figure 5d).

The ranking of the nutrient losses was N > K > S > P in both countries (Figure 5). In this study, the nutrient losses by residues burning largely depend on wheat production values in both countries. Similarly, other research studies showed that the nutrients in aboveground biomass can also undergo large volatilization and convective losses during burning [55,57]. Kumar et al. [55] estimated that the burning of rice residues results in annual nutrient losses in Punjab up to 3.85 million tons of organic carbon and 59, 20, and 34 thousand tons of N, P, and K at the aggregate, respectively.

In this contribution, the potential of wheat residues burning and its agro-environmental impacts on soil quality were investigated, taking into account sustainability criteria, greenhouse gases emission, and energy losses. In conclusion, the current study demonstrates a robust interdependence between wheat residues burning and environmental effects in both developed and developing countries. In Iran, wheat production increased during 1969–2018, which caused an increase in the wheat residues burning and then GWP, while these trends were inverse for Italy. Similarly, the GHGs emission and energy losses, as affected by wheat residues burning, linearly increased in Iran and decreased in Italy with time. Although the burning of wheat residues resulted in annual nutrient (nitrogen, potassium, sulfur and phosphorus) losses in both countries, the results confirmed that replacing the wheat residues burning with appropriate residues management led to declining nutrient losses in Italy and consequently may influence agricultural sustainability.

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