Chapter

Effect of Balanced and Integrated Crop Nutrition on Sustainable Crop Production in a Classical Long-Term Trial

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Abstract

The classical long-term trial at Hanninghof was established in 1958 on loamy sand soil in Duelmen, Germany to study the long-term effects of different nutrient management strategies. The impact of balanced mineral fertilizer application and integrating farmyard manure (FYM) with mineral fertilizer on indicators of sustainable crop production are evaluated in comparison to unbalanced nutrition. Crop rotation since 1958 was potato, followed by winter rye and oat. After 2008, the rotation was silage maize, winter rye, and potato to adjust the trial to current farm practice, but the treatments remained the same: a control plot without fertilizer; FYM alone; and mineral P + K, N, N + P, N + K, N + P + K, and N + P + K + Mg fertilizers with and without FYM. The effect of each treatment on crop yield, revenue, sustainable yield index, water and nutrient use efficiencies, soil nutrient and carbon contents, and soil pH are presented. Evaluation of the 62 years data shows that unbalanced nutrition caused by omitting nutrients and application of only FYM as organic nutrition reduced crop yield and revenue, led to inefficient use of resources and nutrients, and a depletion of soil fertility with negative implications on sustainability. Application of mineral fertilizer N + P + K + Mg as the balanced nutrition and supplementing FYM with mineral fertilizer as the integrated nutrition had social, economic and environmental benefits indicating sustainable crop production.

Keywords: balanced nutrition, integrated nutrition, soil fertility, sustainable crop production

1. Introduction

Long term trials (LTTs) are conducted on a stationary site for many years and classified as Young, Medium, and Classical, respectively in age less than 20, 20–50, and older than 50 years [1, 2]. They are appropriate to study the sustainability of crop production which is defined as the ability to produce the required crop yield and quality to satisfy present and future food demand, while protecting the environment. Population and economic growths are estimated to result in a 50% increase in the demand for food by 2050 with little scope to expand the agricultural area [3]. Thus, a sustainable increase of crop yield per area is required to meet the rising demand for food.

This target requires improvement of yield through integration of productive crop varieties, fertile soils, adequate water supply, sufficient plant nutrients with efficient use, protection of crops against weeds, diseases and pests, and post-harvest care [4]. Continuous crop yield increases are mostly determined by the improvement of crop varieties. Improved crop varieties require advanced cultivation practices, best nutrient application strategies, and pre- and post-harvest crop protection [5]. Improvement of crop nutrition is one of the essential management factors to increase yield.

A trial conducted in India for example, showed that improved cultivars along with balanced nutrition resulted the highest yield increase in range of 92 to 204% over the farmer's practice [6]. Vyn (2014) said "global maize yields will not be able to continually boost to achieve food security without providing adequate and balanced nutrients" [7]. The synergy between improved genetic and adequate nutrient supply sustained the increased production of rice and wheat for nearly three decades in India; however, in recent years the high productivity is stagnating or declining in spite of supplying increased N, P and K fertilizer rates, because of unbalanced nutrient application [8].

Soil fertility is the major environmental factor and is viewed as the capacity of the soil to retain, cycle, and supply essential nutrients to support crop growth for a long time [9]. The relationship of nutrient application and soil fertility is reliably studied in the LTTs, because soil fertility develops gradually and therefore, evaluation of its effect on crop production requires monitoring over a long time and a proper documentation of data [10]. The LTTs are the right tool to study changes that can take decades before they become visible, for example: trends of crop yield and effects of the environment on agriculture or vice versa [11]. Since agriculture is removing nutrients from the soil an efficient replacement of nutrients back into the soil is required to sustain crop yields [12]. The target to increase crop yield per area requires avoiding nutrient mining, maintaining soil fertility, and minimizing nutrient loss to protect the environment.

Balanced nutrition is the key to sustainable crop production and maintenance of soil health with both economic and environmental benefits. An unbalanced nutrition results in a low nutrient use efficiency, poor economic returns, and high environmental pollution [13]. The Law of the Minimum states: "If one of the essential growth factors/nutrient is deficient, plant growth will be limited even when all other factors/nutrient are sufficiently available that growth is improved by the application of deficient factor/nutrient". Dev (1998) viewed the balanced nutrition as "a best management practice refer to the application of essential nutrients in optimum quantity and proportion including proper application methods and time for the specific soil, crop, and climate conditions" [14]. It ensures accessibility of crops to an adequate nutrient supply at every growth stage to avoid over or under-supply enabling the crop for a strong, healthy and productive growth while minimizing pollution of the environment [15]. It can be further defined as the application of right sources of nutrients in an adequate amount and ratio with optimum methods at the time required to support healthy crop growth to increase yield and quality.

Integrated crop nutrition is the combined application of organic and mineral fertilizers to increase yield and to improve soil fertility. Organic fertilizer alone can often not fully satisfy the nutritional demand of crops, because it contains inadequate and unbalanced nutrients [16]. It may not be available in sufficient quantities. Supplementing organic fertilizer with mineral fertilizer is needed to improve nutrient availability and increase crop yield.

The Hanninghof classical LTT was established in 1958. Three strategies of crop nutrition are compared: (1) Balanced nutrition, (2) Integrated nutrition, the combination of farmyard manure (FYM) with mineral fertilizer, and (3) Organic nutrition, application of FYM only. The effects of these different treatments on crop yield, economic revenue, sustainable yield index, water and nutrient use efficiencies and soil nutrient content, organic matter and pH are measured to evaluate social, economic, and environmental benefits of best strategies of nutrient application. The objective of the trial is to study the long-term impacts of different nutrient management on parameters of crop productivity and soil fertility to quantify sustainable crop production.

2. Materials and methods

2.1 Location and history

The Hanninghof LTT is one of few classical LTT in the world. It is located near Duelmen in Western Germany. Crop rotation started with potato cultivation in 1958, followed by winter rye in 1959 and oat in 1960. The sequence of rotation changed to silage maize, winter rye, and potato after 2008 to adjust the trial to current agricultural practices, but the basic setup of the trial remains the same. During 1958–2020, potato, winter rye, oat, and silage maize were cultivated respectively 19, 21, 17, and 5 times.

2.2 Soil and climate

The trial was established on a loamy sandy soil with the following initial soil parameters: P_2O_5 13.3 mg (100 g) $^{-1}$, K_2O 10 mg (100 g) $^{-1}$, Mg 2.1 mg (100 g) $^{-1}$, organic carbon 2.1%, N total 0.1%, and pH 5 at soil depth 0–30 cm. The annual rainfall and yearly mean air temperature were, respectively 469–1273 mm and 7.7–12.3°C during 1958–2020.

2.3 Layout

The trial is a two-factorial experiment in a split-plot with a randomized complete block design. The cultivated area of the trial is 0.3 ha (72 m × 42 m). The field is split into two parts, one receiving FYM every 3 years during 1958–2008 and yearly since 2009 and the other part is without FYM. Each of the two parts is subdivided into 32 plots, i.e., 64 plots in total. The gross area of a plot is 4.5 m × 10.5 m with a harvested area of 3.5 m × 9.5 m to avoid the border effect.

2.4 Treatment

Sixteen treatments were established as shown in **Table 1**. Each treatment is replicated four times and randomly assigned to plots. In 1960, a treatment with N only (#8 and #16) was established. Since the trial was already ongoing for 2 years, new control treatments were assigned. The new control treatments (#7 and #15) are omitted from data evaluation (**Table 1**), because they were not different from treatments #2 and #10.

FYM plus mineral fertilizer		Mineral fertilizer without FYM	
#	Treatments	#	Treatments
1	FYM + N + P	9	N + P
2	FYM without mineral fertilizers	10	Control (without mineral fertilizers)
3	FYM + N + K	11	N + K
4	FYM + N + P + K	12	N + P + K
5	FYM + P + K	13	P + K
6	FYM + N + P + K+ Mg	14	N + P + K+ Mg
7	FYM without mineral fertilizers	15	Control (without mineral fertilizers)
8	FYM + N	16	N

Table 1.
Description of treatments.

2.5 Nutrient application

Mineral fertilizer nitrogen (N), phosphorous (P), potassium (K), and magnesium (Mg) rates were the same for the treatments with and without FYM during 1958–2008. FYM was applied as pig manure at a rate of 25 t ha^{-1} once every 3 years in spring. Nutrient content of FYM is calculated based on 7 kg N-total, 6.7 kg P_2O_5, 7.2 kg K_2O and 2.2 kg MgO per ton of pig manure [17].

After 2008, the trial was adjusted to reflect recent crop rotation and nutrient application. Oat was replaced by silage maize. FYM was replaced by cattle slurry and applied annually at the rate of 30, 20, and 20 m^3 ha^{-1}, respectively during silage maize, winter rye, and potato cultivation. The nutrient content of FYM was considered in the total nutrient application rate to make the nutrient input with FYM and without FYM comparable. The nutrient content of cattle slurry was analyzed every year in the laboratory. Nutrient rates for potato, winter rye, oat and silage maize are given in **Table 2**.

N, P, K, and Mg from mineral fertilizers were applied as calcium ammonium nitrate (CAN) with 4% MgO, triple supper phosphate, potassium chloride, and magnesium nitrate respectively. Since 2013, N was applied as CAN with 6% S to avoid 4% MgO content of CAN that resulted in a reduction of the treatment effect of Mg on crop yield. Since 1958, lime (CaO) was applied to the whole field at a rate of 1000 kg ha^{-1} every 3 years to stabilize soil pH. Since 2009, S fertilizer was applied every year at a rate of 20 kg S per ha on the whole field to avoid S deficiency. Pig manure was applied 10 days before potato planting during 1958–2008. Since 2009, cattle slurry was applied 10 days before silage maize and potato planting, and at the early vegetative stage of winter rye. Mineral fertilizer N was applied once at planting for potato. It was split applied for winter rye at early vegetative, stem elongation, and booting; for oat at seeding and booting; and for maize at seeding and early vegetative growth stages. P, K and Mg mineral fertilizers were applied once at the planting of potato, oat, and silage maize; and at the early vegetative stage of winter rye cultivation.

2.6 Analysis of crop and soil parameters

Crop fresh and dry matter yields were recorded. The crop samples were dried in a drying cabinet at 70°C. Soil samples were collected before crop seeding (planting) at

Crop	Years	FYM + mineral fertilizer (kg ha $^{-1}$)				Mineral fertilizer alone (kg ha $^{-1}$)			
		N	P_2O_5	K_2O	MgO	N	P_2O_5	K_2O	MgO
Potato	1958–1979	175 + 100	168 + 90	180 + 160	55 + 50	100	90	160	50
	1979–2006	175 + 140	168 + 90	180 + 160	55 + 50	140	90	160	50
	2013–2018	68 + 88	29 + 27	83 + 77	18 + 10	140	60	160	30
Rye	1959–1980	0 + 60	0 + 90	0 + 120	0 + 50	60	90	120	50
	1980–2007	0 + 140	0 + 90	0 + 120	0 + 50	140	90	120	50
	2010–2018	77 + 100	31 + 31	85 + 41	20 + 11	150	60	120	30
Oat	1960–2008	0 + 100	0 + 90	0 + 120	0 + 50	100	90	120	50
Maize	2009–2016	132 + 87	55 + 20	135 + 20	35 + 9	170	60	150	38
	2019–2020	78 + 125	35 + 27	95 + 104	24 + 14	200	75	230	44

Table 2.
Nutrient application rate per year during 1958–2020.

0–30 cm soil depth from all 4 plots of each treatment and mixed thoroughly to obtain a uniform sample. Macro and micro nutrient concentrations in the tuber, grain, straw and silage of crop and soil nutrient content, organic matter and pH were analyzed as follows:

N content of crop: Crop dry matter was digested with sulfuric acid and catalyst tablet to produce 50 ml of filtered samples. The N concentration of the sample was determined by continuous flow analysis based on standard operation procedures according to the Kjeldahl method.

Macro and micro nutrients content of crop: The dried crop samples were digested with nitric acid by direct heating in the microwave. The macro and micro nutrient in the digested samples were determined on the ICP-OES (inductively coupled plasma-optical emission spectrometry) according to standard operation procedures.

Soil P and K content: The air-dry soil samples were sieved via 2 mm sieve and mixed with 100 ml calcium acetate and lactate solutions and shaken on the flat shaker for 90 minutes. The plant available P and K contents of filtrate of the soil samples were determined by ICP.

Soil organic matter: The total organic carbon (TOC) was determined by Vario Select Elementary device. The TOC content was calculated from the integral values of the measurement peaks and the calibration coefficients.

Soil pH: The air-dried soil samples were sieved on 2 mm sieve and pH was measured in a 0.01molar $CaCl_2$ solution after 1 hour by pH electrode.

2.7 Data organization and evaluation

Crop yield data were converted to cereal units to aggregate data of different crops along 62 years. The potato tuber, winter rye grain, oat grain, and maize silage yield were multiplied by respectively 0.22, 1.01, 0.85, and 0.18 to convert into cereal unit [18]. The significance differences between average crop yield of treatments were analyzed statistically. The yield data were grouped into 12 periods (1958–1963, 1963–1968, 1968–1973, 1973–1978, 1978–1983, 1983–1988, 1988–1993, 1993–1998, 1998–2003, 2003–2008, 2008–2014, and 2014–2020) to evaluate the trend of crop yield, because crop varieties remained unchanged during 5- or 6-years interval per each period with similar effect on yield.

Crop yields data (1958–2020) were converted to revenue (economic yield) by multiplying annual yields with historical crop prices [19]. The cost of mineral fertilizer was obtained by multiplying the mineral fertilizer rate with historical prices [20]. FYM was regarded free of cost. The economic evaluation included mineral fertilizers cost only, because all other costs of crop production were considered equal for all treatments. Economic benefit ($USDha^{-1}$) = crop revenue - mineral fertilizer cost.

Sustainable yield index (SYI) was calculated according to Singh et al. (1990) based on the standard deviation of mean to evaluate the stability of yield [21, 22]. SYI = average yield (AY) of treatments minus standard deviation (SD) divided by maximum yield (MY) in different years and treatments.

Green water use efficiency (WUE) was calculated according to Sharma et al. (2013) based on historical rainfall data recorded at the LTT site [23]. WUE (kg yield per mm rainwater) = Yield ($kgha^{-1}$) divided by cumulative rainfall (mm) from sowing to harvest.

Nutrient use efficiency was calculated according to partial factor productivity [24]. N use efficiency (%) = N removal with N fertilized crop divided by N fertilizer rate and multiplied by 100. The calculation was done similarly for P and K fertilizer use efficiencies.

The soil fertility is measured by nutrient content, organic matter and pH. The soil parameters were organized with a three-year moving average. The changes in soil fertility were evaluated in comparison to the control treatments and initial values measured in 1958.

3. Results

3.1 Effect of balanced and unbalanced nutrition on crop production and soil fertility

3.1.1 Average agronomic and economic yields

The balanced nutrition (N + P + K + Mg treatment) resulted in the highest average cereal unit yield of 5.4 t and an economic benefit of 1216 $\$ha^{-1}$ (**Figure 1**). The average yield of 5.4 tha^{-1} is low because of the low-yielding varieties at the early decades of the trial and a low water holding capacity of the sandy soil at the site. Without fertilizer application, the yield was only 1.9 t and 469 $\$ha^{-1}$. The application of P and K without N showed almost no increase in crop yield, 2.1 t and 404 $\$ha^{-1}$. N fertilizer application but omitting P, K, and Mg resulted in a yield of 3.8 t and 831 $\$ha^{-1}$. The yield declines due to omission of K + Mg, P + Mg, and Mg were respectively 18%, 9%, and 7% and the corresponding income loss were 315$, 70$ and 89$ (**Figure 1**). Omitting K fertilizer leads to a higher yield reduction than omitting P fertilizer because of decreasing K supply from the soil (**Figure 2**). The yield and income loss due to the omission of P were rather small because of the high P content of the soil (**Figure 3**). Application of CAN with 4% MgO during 1958–2013 as a source of N resulted in low effect of omitting Mg fertilizer on crop yield. Application of only FYM decreased yield by 38% and 275$\$ha^{-1}$ (**Figure 1**).

3.1.2 Trend of average agronomic and economic yields

Crop varieties improved during 62 years of the trial which can be seen in the yield increase over time in almost all treatments. The balanced nutrition (N + P + K + Mg treatment) resulted in the highest yield and income compared to nutrient omissions

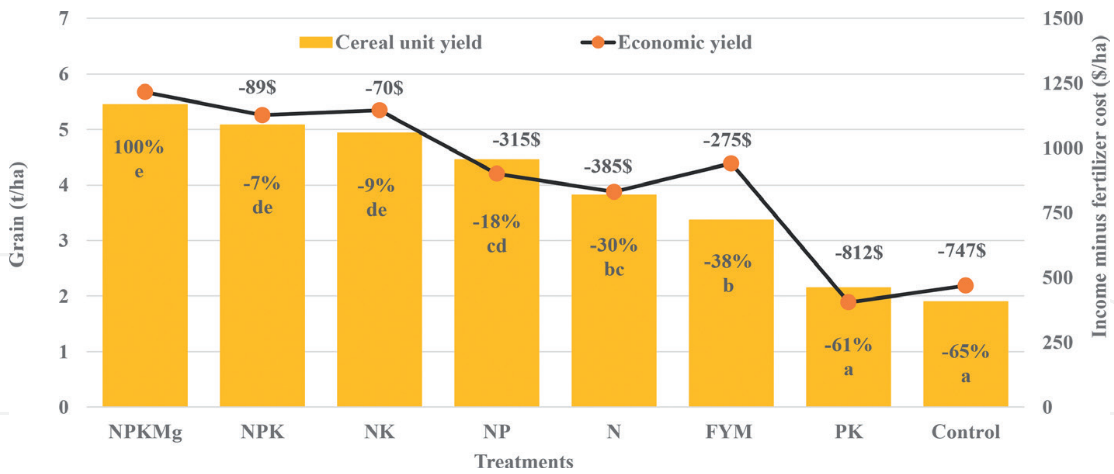

Figure 1.
Effect of balanced nutrition, omitting nutrient, and FYM on average crop yields (n = 62 years); Grain yield with the same letters showed the insignificant difference.

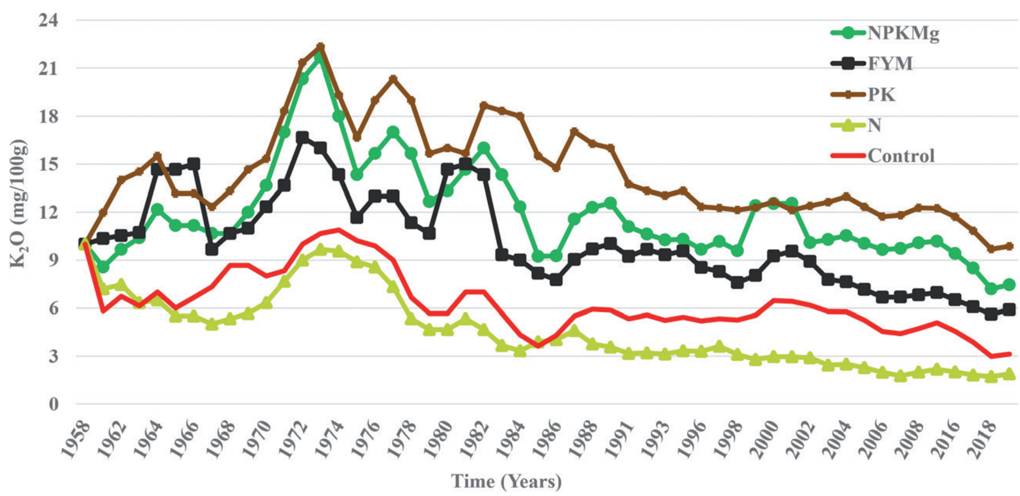

Figure 2.
Effect of balanced nutrition, omitting nutrient, and FYM on soil K content in 0–30 cm depth.

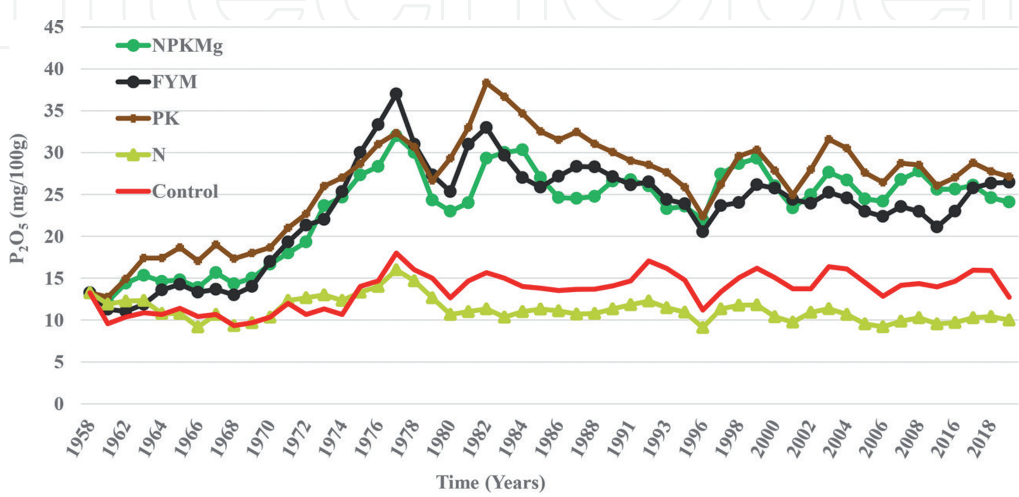

Figure 3.
Effect of balanced nutrition, omitting nutrient, and FYM on soil P content in 0–30 cm depth.

or FYM application without mineral fertilizer (**Figures 4** and **5**). Before 1980, the N fertilizer rate was insufficient to provide the N demand of potato and winter rye. The low N rate of 100 kgha^{-1} for potato and 60 kgha^{-1} for rye cultivation during1958–1980 (**Table 2**) and reduction of potato yield by nematodes infection in 1973–1982 resulted in decreasing yields during 1968–1980. Since 1980, increasing N rate and cultivating nematode resistance potato reversed the trend of decreasing yields. Improvement of crop variety resulted in increasing yields and income in all treatments, however declining cereal prices during 1990–2003 (data not shown) resulted in decreasing crop economic yield during 1993–2003. Compared to the income at the initial phase (1958–1963), the balanced nutrition increased crop income by 1981 \$ha^{-1} at the final (2014–2020) time interval (**Figure 5**).

3.1.3 Sustainable yield index (SYI) and green water use efficiency (WUE)

SYI indicates the stability of crop yields in the long run. The high index shows the low variation of yield increase over years. Application of mineral fertilizers N + P + K + Mg increased SYI and WUE of crop. Omitting nutrient and application

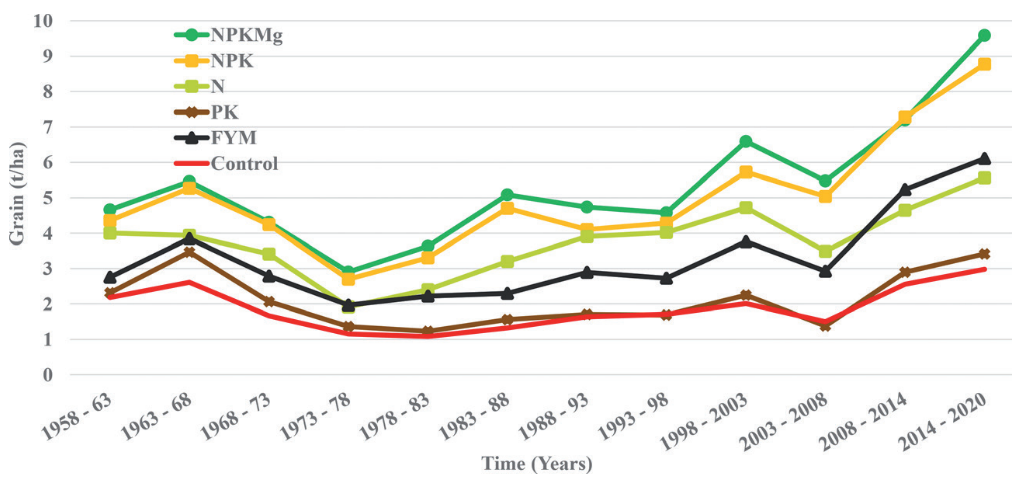

Figure 4.
Effect of balanced nutrition, omitting nutrient, and FYM on the trend of average yield.

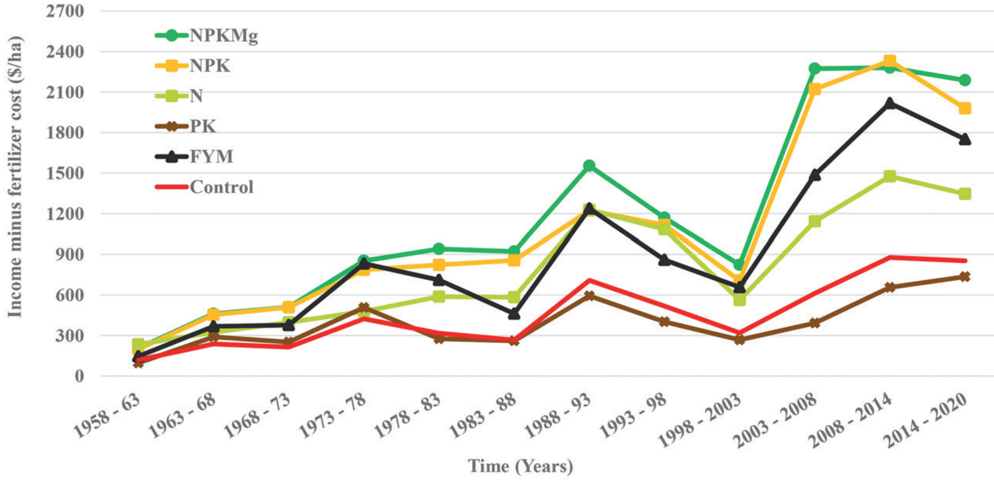

Figure 5.
Effect of balanced nutrition, omitting nutrient, and FYM on the trend of average economic yield.

of only FYM decreased SYI and WUE compared to the balanced nutrition. The WUE was reduced by 63%, 34%, and 7–59%, respectively at without any fertilizer, application of only FYM, and omitting nutrients compared to the N + P + K + Mg treatment (**Figure 6**). The reduction of WUE is directly related to the decline in crop yield because of nutrient omission and application of only FYM.

3.1.4 Nutrient use efficiency

Nitrogen use efficiency (NUE) at the balanced nutrition (N + P + K + Mg) treatment was 77%. Any lack of nutrients reduced the NUE to 49% - 73% (**Figure 7**). P use efficiency (PUE) at the balanced nutrition was 49%. Omitting Mg, K + Mg, and N + Mg resulted, respectively 46%, 42%, and 25% PUE compared to the N + P + K + Mg treatment (**Figure 7**). The balanced nutrition resulted in the highest K use efficiency (KUE) of 84% compared to omitting nutrients and application of only FYM. The KUE at omitting Mg, P + Mg, and N + Mg fertilizers and only FYM

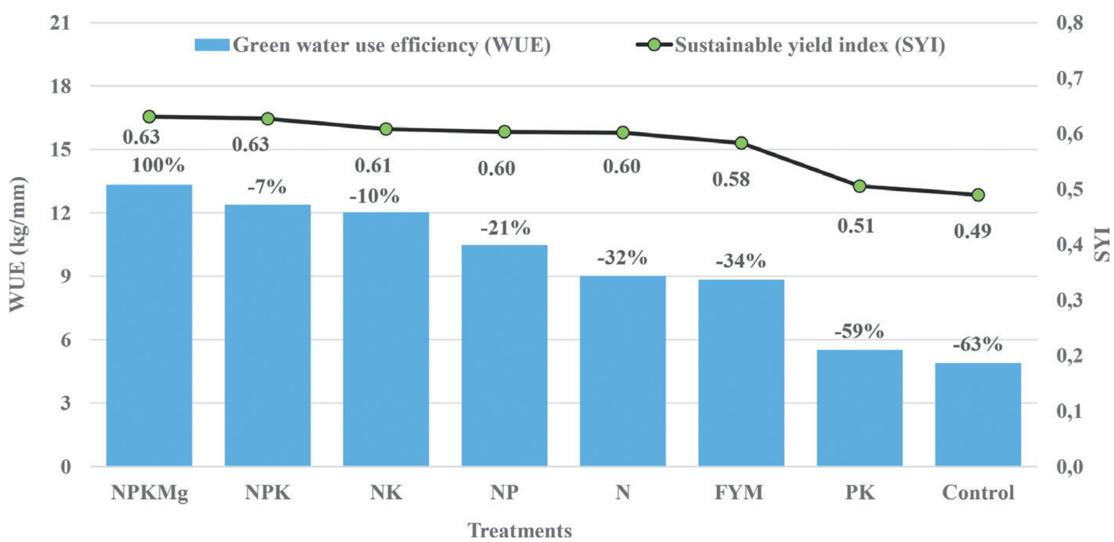

Figure 6.
Effect of balanced nutrition, omitting nutrient, and FYM on average WUE and SYI of the crop (n = 62 years).

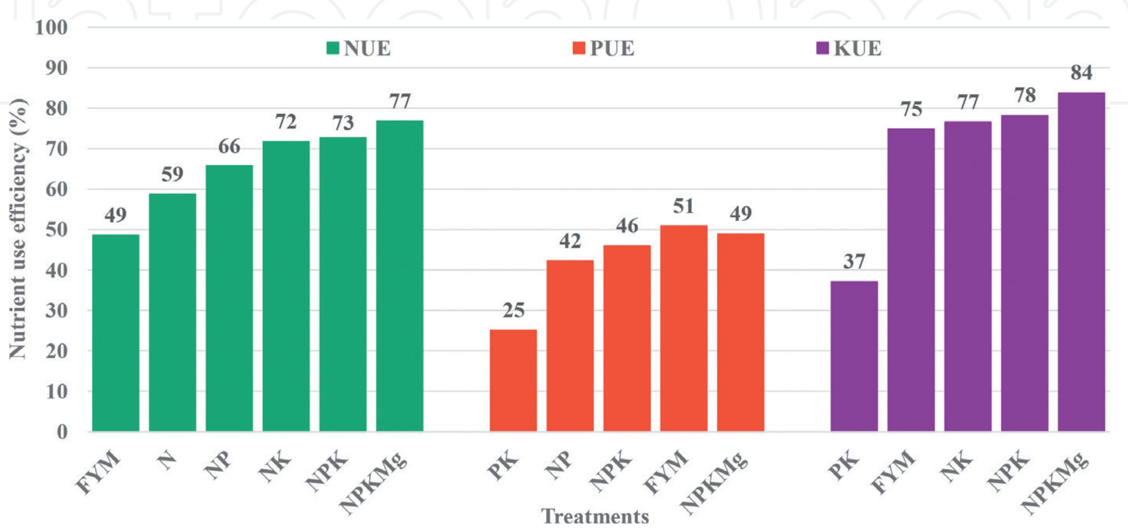

Figure 7.
Effect of balanced nutrition, omitting nutrient, and FYM alone on average N, P, and K use efficiency (n = 62 years).

application were, respectively 78%, 77%, 37%, and 75% (**Figure 7**). The highest nutrient use efficiencies were achieved in the treatment with the balanced supply of nutrients for crop demand. Application of FYM without mineral fertilizer decreased N and K use efficiencies, because of the lower plant availability of N and K in the FYM. P and K fertilizers application without N resulted in a very low PUE and KUE, because of the very low yield and poor recoveries of P and K.

3.1.5 Soil P_2O_5 and K_2O contents

P and K fertilizers application affects soil P_2O_5 and K_2O content. The balanced nutrition (N + P + K + Mg) increased soil P_2O_5 and maintained the soil K_2O in comparison to the omission of P and K respectively.

The P_2O_5 content of loamy sand soil on arable land is classified as 'very low' (below 3), 'low' (4–9), 'medium' (10–18), 'high' (19–32), and 'very high' (above 33) mg P_2O_5 per 100 g soil at 0–30 cm depth [25]. At the start of the trial the soil P content, as well as the K level were therefore classified as medium. P fertilizer application increased soil P_2O_5 content toward very high during 1958–1983: the inadequate N rate during 1958–1980 (**Table 2**) and the limited potato growth in 1973–1982 caused a low crop yield (**Figure 4**) that resulted in an accumulation of P fertilizer in the soil. Increased crop yield after 1982 due to increased N fertilizer rate and cultivating potato variety resistance to nematodes reduced soil P_2O_5 content during 1984–1996. P fertilizer application generally increased soil P_2O_5 content to 'high' level, but omitting P fertilizer reduced the soil P_2O_5 content compared to the initial measurement in 1958 (**Figure 3**).

The K_2O content of loamy sand soil on arable land is classified as 'very low' (below 3), 'low' (4–9), 'medium' (10–18), 'high' (19–32), and 'very high' (above 33) mg K_2O per 100 g soil at 0–30 cm depth [25]. Application of K fertilizer-maintained soil K_2O content at the 'medium' range, while the omission of K fertilizer decreased soil K_2O content to the 'low' level (**Figure 2**). Application of K fertilizer increased the soil K_2O content during the early decades, because of low K removal from the soil. The decreasing soil K_2O content after 1981 was generally driven by combined effects of increased K removal from the soil with high crop yield and loss of K by leaching on sandy soil.

A low crop yield (**Figure 1**) produced a low PUE and KUE (**Figure 7**), at P + K mineral fertilizers application without N, resulted in the highest soil P_2O_5 and K_2O contents (**Figures 2** and **3**). Soil P_2O_5 and K_2O analysis at 30–90 cm in 1987, 2008, and 2018 showed residual P and K fertilizers movement below 30 cm depth. P + K mineral fertilizers application without N increased the soil P_2O_5 and K_2O contents respectively by 43% and 49% in 30–60 cm and by 48% and 96% in 60–90 cm depth compared to the application of N + P + K mineral fertilizers (data not shown).

3.1.6 Soil organic matter and soil pH

Improvement of soil organic matter positively influences soil fertility through its impact on the chemical, physical, and biological properties of a soil. The soil organic matter was measured as soil C (carbon) content. The soil organic C decreased in comparison to the initial value of 2.1% measured in 1958, because crop residues were removed from the field during 1958–2009. It was slightly increased with mineral fertilizer and FYM application compared to the treatment without any fertilizer (**Figure 8**). During 1959–1973, the soil organic C was not measured.

The soil pH was optimized by lime application to avoid the negative effect of pH on nutrient availability. Lime (CaO) applied every 3 years to the whole field at 1000 kgha^{-1} increased soil pH compared to the initial pH measured in 1958 (**Figure 9**).

3.2 Effect of integrating FYM with mineral fertilizer on crop production and soil fertility

3.2.1 Average agronomic and economic yields

Application of FYM plus mineral fertilizer increased yield and income. The highest yield was measured at 6 tha^{-1} in the treatment of FYM plus NP fertilizer. FYM application without mineral fertilizer as organic nutrition only, decreased yield by 44% (**Figure 10**). Application of FYM + N, FYM + NP, FYM + NK, FYM + NPK, and FYM + NPKMg achieved similar yield levels, but FYM + PK fertilizer significantly decreased yield and income due to inadequate availability of N applied as FYM in the treatment. Integrating FYM with NK fertilizer resulted in the highest income measured at 1433 \$ha^{-1} (**Figure 10**). The economic yield at FYM + NP treatment was

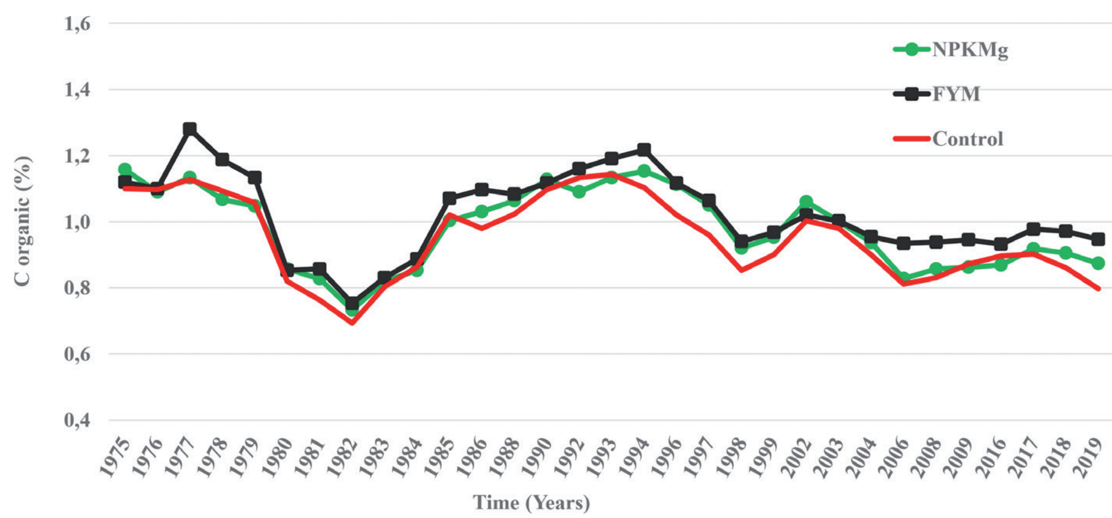

Figure 8.
Effect of balanced nutrition, omitting nutrient, and FYM on soil carbon content in 0–30 cm depth.

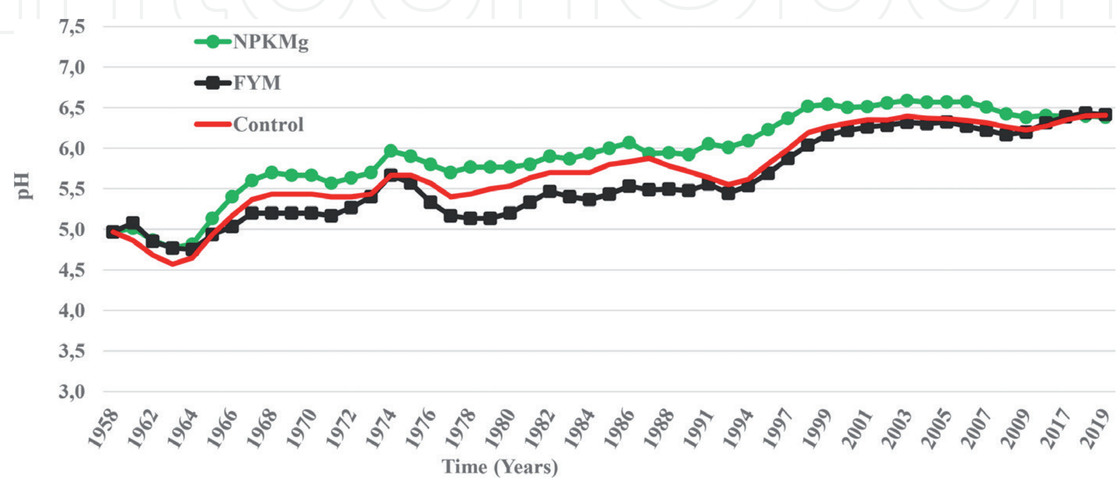

Figure 9.
Effect of balanced nutrition, omitting nutrient, and FYM on soil pH in 0–30 cm depth.

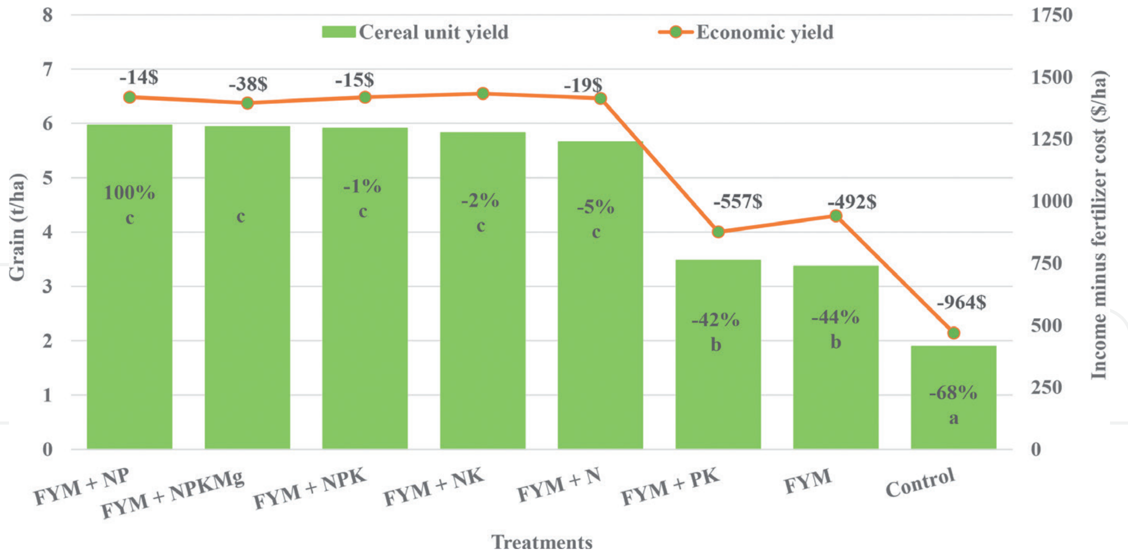

Figure 10.
Effect of integrated nutrition and FYM on average crop yields (n = 62 years); Grain yield with the same letters showed the insignificant difference.

14 $ lower than the economic yield at FYM + NK, because the historical P fertilizer price was higher than K fertilizer price (data not shown). Application of only FYM significantly decreased yield and income, because of the insufficient availability of nutrients in the FYM for the crops.

3.2.2 Trend of average agronomic and economic yields

Improvement of crop varieties during the 62 years of the trial resulted in increasing yield and income trends in all the treatments. The integrated nutrition supported the highest yield and income compared to FYM application only (**Figures 11** and **12**). The decline in yield during 1968–1980 was caused by the low N fertilizer rate in1958–1980 and the reduction of potato growth by nematodes infection in 1973–1982. Increased N fertilizer rate after 1980 and cultivating nematode resistance variety after 1982 reversed decreasing yield levels. The yield was high at integrated nutrition treatment because nutrients were balanced and adequately available compared to only FYM

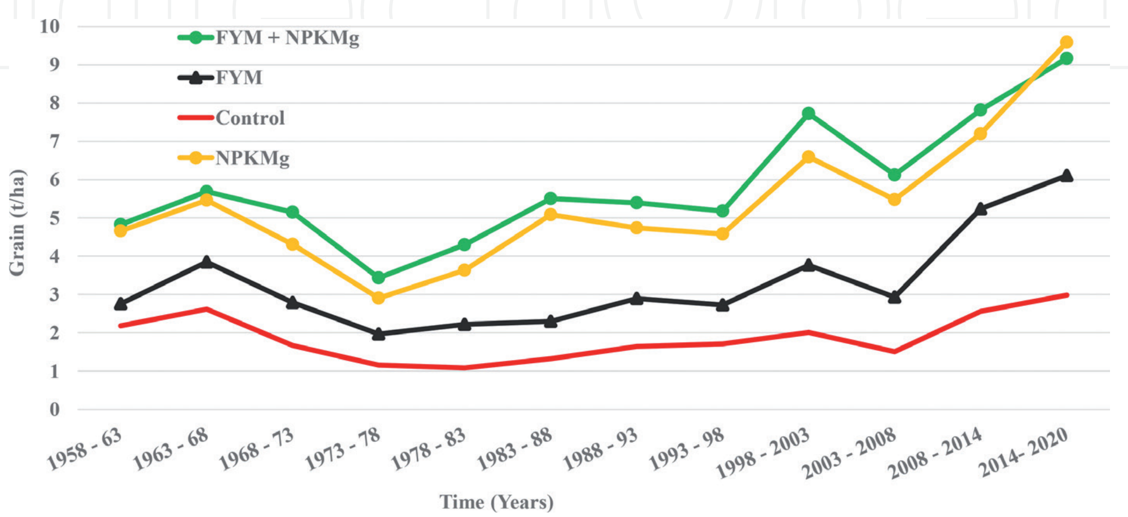

Figure 11.
Effect of integrated nutrition and FYM on the trend of average cereal unit yield.

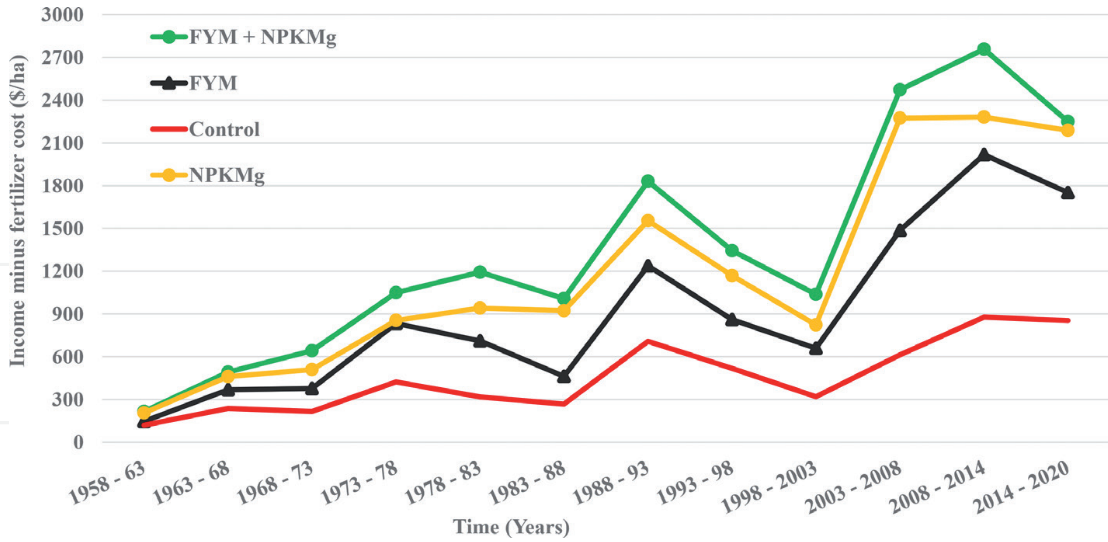

Figure 12.
Effect of integrated nutrition and FYM on the trend of average economic yield.

application. Crop yield and income at integrated nutrition was even higher than at the balanced nutrition (NPKMg) because until 2008, the treatments with FYM received the nutrients from the FYM in addition to nutrients from the mineral fertilizer.

3.2.3 Sustainable yield index (SYI) and green water use efficiency (WUE)

The sustainability of crop production is measured by SYI. A high or low index indicates the level of variations in yield. It is measured as the standard deviations and it is seen as an indicator for sustainability. Nutrient management influences the long-term yield stability. Application of FYM plus mineral fertilizers increased SYI and WUE of the crop (**Figure 13**). WUE decreased by 67% without any fertilizer and by 40% at only FYM compared to the WUE of integrating FYM with NP fertilizer (**Figure 13**). A reduction of crop yield because of nutrient deficiency resulted in a low SYI and inefficient use of water.

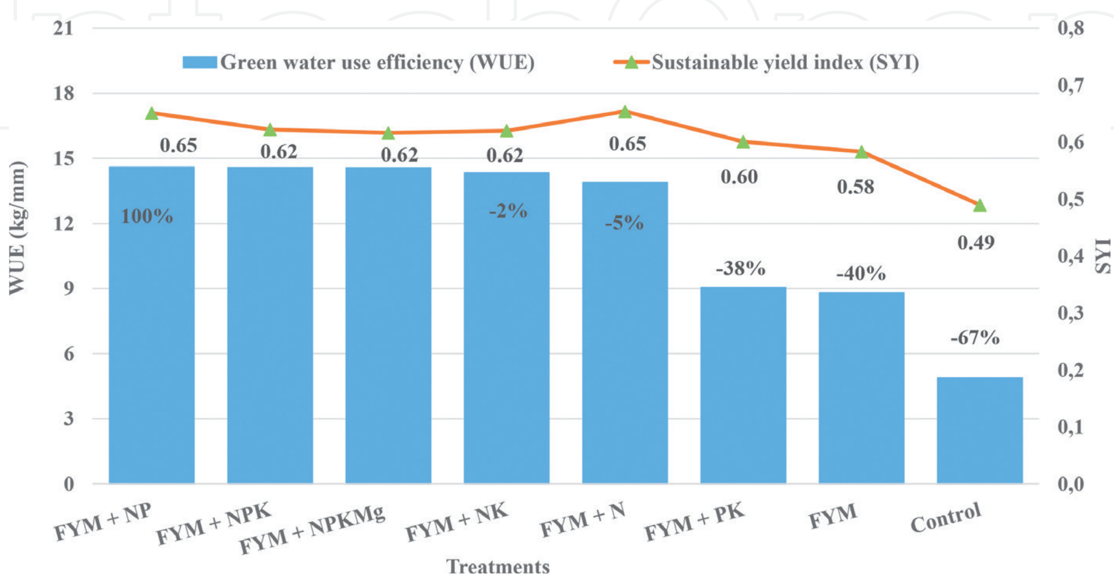

Figure 13.
Effect of integrated nutrition and FYM on average WUE and SYI (n = 62 years).

3.2.4 Nutrient use efficiency

Nitrogen use efficiency (NUE) was 73% at the integrated nutrition treatment (FYM + NP mineral fertilizer). Application of FYM only and FYM plus PK fertilizer decreased NUE to 49% and 51% (**Figure 14**). Low yield (**Figure 10**) due to low N availability in the FYM reduced NUE at the treatments FYM only and FYM plus PK fertilizer. The highest P use efficiency (PUE) of 66% was calculated at FYM + NK fertilizer (**Figure 14**). Low PUE of 51% at the application of only FYM and 32% at FYM plus PK fertilizer were recorded, because inadequate availability of N from FYM reduced yield (**Figure 10**) and P output. Combining FYM with NK or N fertilizer significantly increased PUE. K use efficiency (KUE) was increased to 99% at integrating FYM with NP fertilizer (**Figure 14**). It was decreased to 75% at the application of FYM only and decreased to 47% by omitting mineral nitrogen at FYM plus PK. The nitrogen deficiency in the FYM plus PK fertilizer treatment decreased yield and limited K recovery.

3.2.5 Soil P_2O_5 and K_2O contents

The soil P_2O_5 content indicates the capacity of a soil to supply P for crop growth and it is affected by P fertilizer application. It was increased during 1958–1983, because of inadequate N fertilizer rates during 1958–1980 (**Table 2**) and low yielding potato from 1973 to 1982 resulted in an accumulation of P fertilizer in the soil. Increased crop yield after 1982 due to increased N fertilizer rate and cultivating nematode resistance variety caused a decreasing trend of soil P_2O_5 during 1984–1996 compared to the highest soil P_2O_5 content recorded in1977 and 1982. Integrating FYM with P fertilizer increased soil P_2O_5 content to the 'very high' level. FYM only and FYM plus N or NK fertilizers increased soil P_2O_5 to the 'high' level compared to the initial soil P_2O_5 measured in 1958 (**Figure 15**).

Integrated nutrition and application of FYM only increased soil K_2O during 1958–1980 compared to the initial soil K_2O content (**Figure 16**), it was caused by low crop yield resulting in an accumulation of residual fertilizer K in the soil. The decreasing trend of soil K_2O after 1980 was caused by a combined effect of increased K removal from the soil through high crop yields (**Figure 10**) and K loss by K leaching

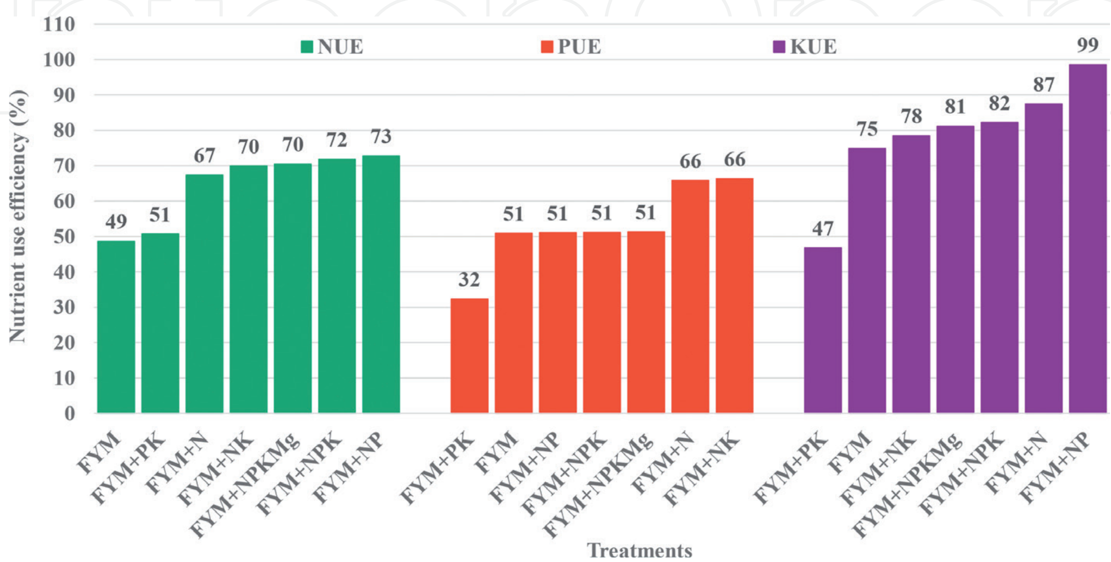

Figure 14.
Effect of integrated nutrition and FYM alone on average N, P, and K use efficiency (n = 62 years).

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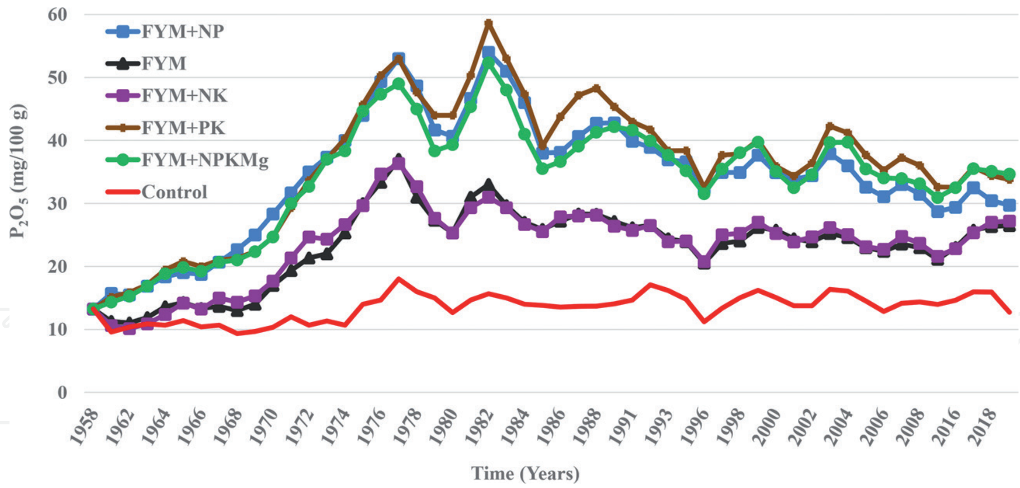

Figure 15.
Effect of integrated nutrition and FYM on soil P content in 0–30 cm depth.

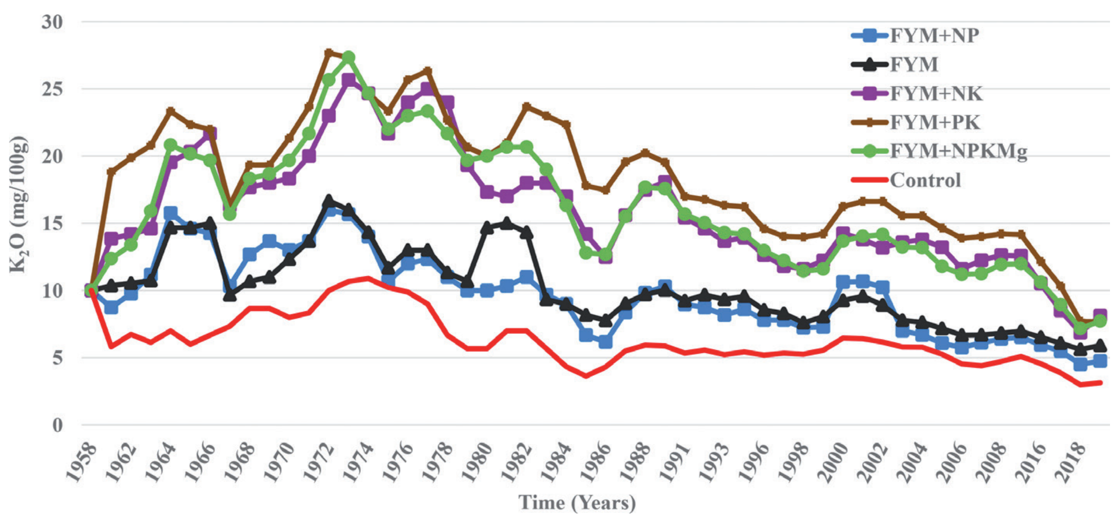

Figure 16.
Effect of integrated nutrition and FYM on soil K content in 0–30 cm depth.

on sandy soil. FYM combined with K fertilizer generally maintained soil K_2O content, but FYM only and FYM plus N or NP fertilizers depleted soil K_2O to the 'low' level after 1982 (**Figure 16**). The negative input–output balance caused a K-mining of the soil of 5 kg K per ha and year at FYM alone, and 41, and 30 kg K per ha per year, respectively at FYM plus N, and FYM plus NP fertilizers and decreased soil K_2O content. FYM plus PK fertilizer resulted in the highest soil K_2O content (**Figure 16**) due to low crop yield (**Figure 10**) and inefficient use of K fertilizer (**Figure 14**). Analysis of soil K_2O in 30–90 cm in 1987, 2008, and 2018 showed residual K fertilizer movement below 30 cm depth. The soil K_2O content increased by 37% in 30–60 cm and 22% in 60–90 cm depth at FYM plus PK fertilizer compared to the FYM plus NPK fertilizer (data not shown).

3.2.6 Soil organic matter and soil pH

The soil organic matter improves soil fertility by its influence on the chemical, physical, and biological properties of a soil. It was measured as an organic fraction of soil C. The soil organic C decreased in comparison to the initial value of 2.1%

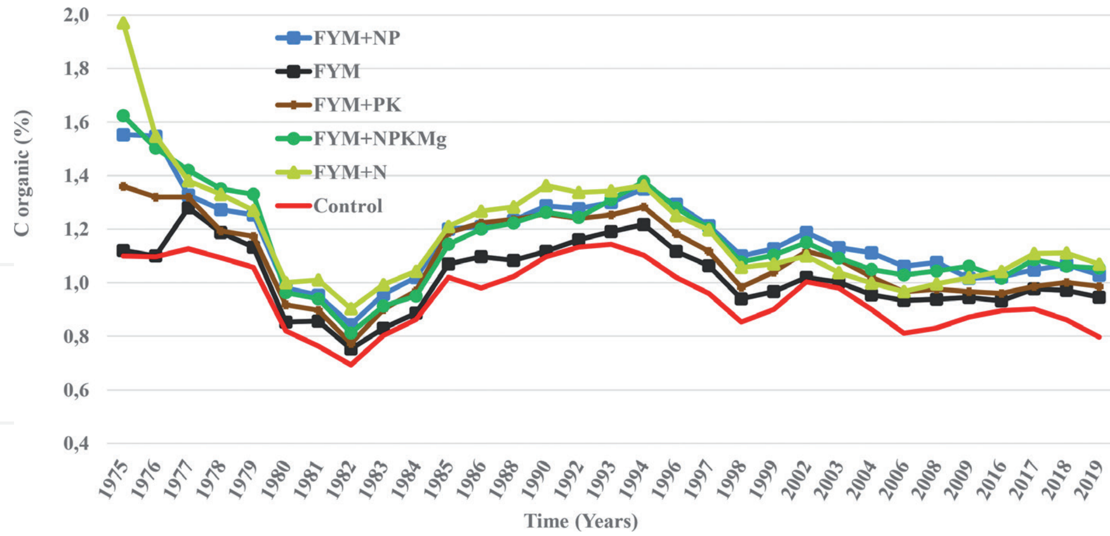

Figure 17.
Effect of integrated nutrition and FYM on soil carbon content in 0–30 cm depth.

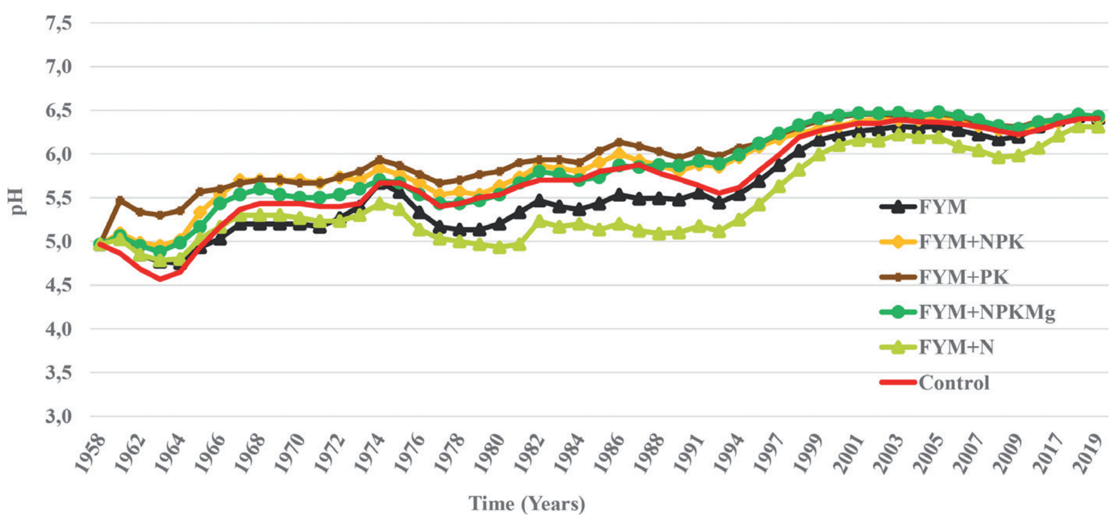

Figure 18.
Effect of integrated nutrition and FYM on soil pH in 0–30 cm depth.

measured in 1958, because crop residues have been removed from the field until 2009. Integrated nutrition increased soil C compared to only FYM application (**Figure 17**). Reduction of crop growth and low root biomass indicated by low yield (**Figure 10**) decreased soil C content at the treatment without any fertilizer. During 1959–1973, the soil organic C was not measured.

Liming of soil every 3 years with 1 tone CaO per ha increased soil pH compared to the initial pH measured in 1958 (**Figure 18**).

4. Discussion

Sustainable crop production can be defined as the agricultural practices that meet human needs for food, is economically viable, while at the same time being environmentally positive [26]. Evaluation of 62 years data of the classical long term trial has shown the importance of nutrient management on all three aspects of sustainability: (1) Improvement of crop yield, sustainable yield index, WUE and soil fertility to produce sufficient food (Social), (2) Profitability of crop production, efficient use of resources, and maintenance of soil fertility to grow the income of farmers (Economic), and (3) Efficient use of nutrients and improving soil fertility to minimize nutrient loss (Economic and Environmental).

4.1 Effect of balanced nutrition on the sustainability of crop production

The data of the trial confirmed that a balanced nutrition increases crop yield, avoids nutrient deficiency, increases nutrient and water use efficiency, protects the environment by minimizing nutrient loss, and improves soil fertility. Chopra et al. (2014) reported similar results [27]. Application of mineral N + P + K + Mg fertilizer as balanced nutrition resulted in the highest yield and income of crop (**Figure 1**). Similar results were reported for potato with N + P + K + Mg + S application [28] and for maize with N + P + K + Mg application [29, 30] as balanced nutrition compared to treatments of unbalanced nutrition. Omitting nutrients reduced crop yield and resulted in an economic loss of between 89 and 812 $\$ha^{-1}$ (**Figure 1**). Dev (1998) and Chander et al. (2012) also reported that omitting nutrients significantly decreased yield and profit of maize, millet, rice, soybean, and wheat [14, 31]. Application of only FYM significantly reduced crop yield and income compared to the balanced nutrition (**Figure 1**). Černý et al. and Dilshad et al. (2010) and Abid et al. (2020) reported a significant reduction of barley, maize, potato, rice, and wheat yields with the application of FYM only compared to N + P + K mineral fertilizer [32–34]. Bhattacharyya et al. (2014) reported a decrease in maize and wheat economic benefit at FYM alone compared to N + P + K fertilizer [35].

Crop varieties improved during the 62 years of the trial and resulted increasing yields. Evaluation of the cereal yield per ha indicates that the average yield was increased by 101% during the latest decade (2010–2020) compared to the average yield measured between 1961 and 1970 for Germany [19]. Fertilizer application is an essential management practices that positively affects yield and income in the long-term. The balanced nutrition of the essential plant nutrients was best nutrient management practice and resulted in the highest yield (**Figures 4** and **5**). Crop yield and income increased during the years 2008 to 2020 were 66% and 1901$\$ha^{-1}$higher than in the earliest years 1958 to1968 (**Figures 4** and **5**). The combined effects of better varieties and fertilizer application improved crop yield and soil fertility during the trial periods (**Figures 2, 3** and **9**). An unbalanced nutrition resulted in yield loss of 6 to 53% or up to 311$\$ha^{-1}$ during the earliest decade, but 8 to 69% (158 to 3075$\$ha^{-1}$) loss during the latest decade. N fertilizer application without PK fertilizer similarly resulted in 86% reduction of maize grain yield during 2001–2006 compared to maize yield at N without PK fertilizer during 1987–1988, because cumulative K releasing power of the soil has depleted 33% in 2003 compared to K releasing power of the soil in 1986 [36]. The high productivity and revenue per area with the balanced nutrition support the social and economic aspects of sustainable crop production.

The long-term application of balanced nutrient positively affects the stability of crop yield [37]. Balanced nutrition (N + P + K + Mg fertilizer) resulted in the highest SYI compared to omitting nutrients (**Figure 6**). Ray et al. (2017) similarly reported the highest SYI with the balanced nutrition (N + P + K + S + Zn fertilizer) compared to the unbalanced nutrition [38]. Application of only FYM decreased SYI by 8% compared to both the N + P + K and N + P + K + Mg treatments (**Figure 6**). Abid et al. (2020), Bhattacharyya et al. (2014), and Malarkodi et al. (2019) reported a reduction of SYI, respectively by 6%, 17% and 5% with only FYM compared to N + P + K mineral fertilizer [34, 35, 39]. The highest SYI was observed at the balanced nutrition and it confirms stable yields as an indicator of sustainability.

Land, solar energy, and water are the major natural resources required to produce crop. Efficient utilization of these resources is necessary for sustainable crop production. Nutrient application is important to increase land and water use efficiency. Reduction of yield because of unbalanced nutrition (**Figure 1**) resulted in inefficient use of land, because more land (1.1 to 1.7 ha) is required to achieve the same yield as on 1 ha of land at the balanced nutrition treatment. The N + P + K + Mg fertilizer resulted in the highest WUE compared to omitting nutrients and FYM application alone (**Figure 6**). Omitting nutrients decreased WUE by 7 to 63%. Chander et al. (2013), Suhas et al. (2013) and Chander et al. (2012) reported similar results [6, 8, 31]. Efficient use of resources is only possible in a balanced application of plant nutrients.

The best practice of nutrient management increases nutrient use efficiency in crop production. The N, P, and K use efficiencies (NUE, PUE, and KUE) of major cereal crops are reported to be between 40 and 65%, 15–25%, and 30–50% respectively at recommended management practices with recommended soil P and K contents [40]. The balanced nutrition (N + P + K + Mg fertilizer) resulted in a high nutrient use efficiency compared to the unbalanced nutrition. The average NUE, PUE, and KUE of crop at the balanced nutrition were, respectively 77%, 49% and 84% (**Figure 7**). Omission of nutrients and application of only FYM decreased nutrient use efficiency by 5–56%, because crop growth and yield were limited by nutrient deficiency. Kumar et al. (2021) reported reduction of nutrient use efficiency by 27–65% for potatoes due to nutrient omission compared to the balanced nutrition [41]. Similar results were reported in Wang et al. (2010) for maize and wheat [42]. Inefficient use of nutrients causes a high cost of production or economic loss and a high risk of environmental pollution.

Physical, chemical, and biological parameters of soil fertility influence the capacity of soil to support crop growth. Nutrient management with its direct impact on nutrient and organic matter contents, pH, and cation exchange capacity of soil supports sustainable crop production. Long-term soil fertility is ensured by balanced nutrition and concurrent application of lime [43]. Omitting P fertilizer decreased soil P content (**Figure 3**). Bhattacharyya et al. (2015) also reported a reduction of soil P content due to P fertilizer omission [44]. K removal without replacement depleted soil K from the medium to the low level (**Figure 2**). Zhao et al. (2014) reported that omitting K fertilizer similarly decreased soil K content at different depths [45]. Balanced nutrition improved soil nutrient content to desirable levels and increased yield with positive impacts on sustainable crop production.

The soil organic matter improves soil water-holding, aeration, nutrient absorption and release, and minimization of leaching and erosion [46]. Application of mineral fertilizer and FYM alone slightly increased soil organic carbon (SOC) compared to the treatment without any fertilizer (**Figure 8**). This was also found by Aula et al. (2016), they reported a significant increase in SOC through the application of NP and NPK fertilizers and FYM compared to without any fertilizer [47]. The only slight increase of organic matter at the application of mineral fertilizer and FYM alone was caused only by root residues (**Figure 1**), because crop residues were removed from the field for more than 50 years. Zhao et al. (2014) reported a significant increase of SOC at mineral NP and NPK fertilizers plus wheat straw compared to NP and NPK fertilizers without straw [45]. The unbalanced nutrition depleted soil organic matter content through a low crop yield. The balanced nutrition improves soil organic matter with positive implications on soil fertility supporting crop growth and yield directly related to sustainable crop production.

4.2 Effect of integrated crop nutrition on the sustainability of crop production

The integrated crop nutrition as the combination of organic and mineral fertilizer contributes: (1) to maintain or enhance soil fertility, (2) to improve nutrient stocks in the soil, and (3) to reduce nutrient loss to the environment by increasing nutrient use efficiency [48]. It improves the availability of nutrient and corrects nutrient imbalances to increase crop yield. Application of FYM plus mineral fertilizers significantly increased crop yield compared to FYM alone (**Figure 10**), which was also reported by Abid et al. (2020) and Mahmood et al. (2017) for maize yield [34, 49] and by Baniuniene and Zekaite (2008) for potato yield [50]. FYM without mineral fertilizer reduced crop yield by 44% and 492\$ha^{-1} (**Figure 10**). Bhattacharyya et al. (2014) similarly reported 47% yield and 59% profit reductions for maize and 49% and 52% for wheat at only FYM application compared to FYM plus NPK fertilizer [35]. The integration of FYM with mineral fertilizer increased yield and income, because it improved nutrient availability required to support the healthy growth of crops.

Integrated nutrition was the best nutrient management practice, because it increased crop yield and income to the highest level (**Figures 10–12**) and it improved soil fertility (**Figures 15–17**). Vasuki et al. (2009) similarly reported that the integrated and balanced use of mineral fertilizer plus organic manures have maintained an increase of crop yield at a higher level over the years [36]. Application of only FYM resulted in a loss of income of 1347 \$ha^{-1} in the latest years (2008–2020) compared to 237 \$ha^{-1} in the earliest years (1958–1968) of the trial, as compared to the treatment of FYM with NK fertilizer during the respective time intervals (**Figure 12**). Hejcman and Kunzova (2010) similarly reported that wheat yield reduction due to application of FYM only was high during the latest decade (1997–2006) and low during the earliest decade (1957–1966) compared to yield at integrating FYM with NPK fertilizer [51]. The synergy between improved varieties and integrated nutrition sustained the increasing yield and income during the long-term, because nutrients have been available in quantity and ratio demanded by high-yielding crop varieties.

The SYI is viewed as a quantitative measurement of sustainability. A high SYI with minimum standard deviation indicates low variability of yield. Integrated nutrition increased SYI compared to the application of FYM alone (**Figure 13**). Integrating FYM with NPK fertilizer similarly increased SYI of maize [34] and sunflower [39] compared to only FYM treatment. Low SYI at only FYM application shows a high variability of yield, while the high SYI at the integrated nutrition indicates sustainable crop production.

Natural resource use efficiency of crop production is increased by improving crop growth. Best nutrient management is therefore needed to achieve efficient utilization of land and water for crop production. Application of only FYM resulted in inefficient land use, because crop yield was 44% lower than at the integrated nutrition (**Figure 10**). Therefore, it requires 1.4 ha of land to achieve the same yield as with FYM plus NP fertilizer on 1 ha, and it decreased WUE by 40% (**Figure 13**). Dubey et al. (2014) similarly reported a 9% reduction of WUE of the crop at only FYM application compared to FYM plus NPK fertilizer [52]. Improvement of land and water use efficiency is an important contribution to sustainable crop production.

Efficient use of nutrients applied as organic plus mineral fertilizers reduces nutrient losses, protects the environment and improves economic return on investment in fertilizer. It was confirmed in the trial data as the highest percentage of crop

NUE, PUE, and KUE were achieved with integrated nutrition. Application of only FYM decreased nutrient use efficiency by 15–24% compared to integrated nutrition (**Figure 14**). Abid et al. (2020) similarly reported a 36% reduction of nutrient use efficiency of maize [34] and Bhattacharyya et al. (2014) reported a 24% and 23% reduction for maize and wheat [35] at only FYM compared to integrating FYM with NPK fertilizer. Application of only FYM was resulted in inadequate and unbalanced availability of nutrients, so that it has been caused a reduction of crop growth and yield, which were ultimately leading to low recovery and inefficient use of nutrients.

Nutrient management improves nutrient availability in the soil and supports soil fertility via its impact on nutrient content, soil organic matter and pH. Integrating FYM with P fertilizer increased soil P_2O_5 content compared to only FYM (**Figure 15**). Malarkodi et al. (2019) and Hejcman and Kunzova (2010) reported similar results [39, 51]. FYM plus K fertilizer-maintained soil K_2O content within the medium range, but only FYM and FYM + NP fertilizer decreased soil K_2O to the 'low' level compared to the initial soil K_2O (**Figure 16**). Application of only FYM similarly depleted soil K_2O compared to FYM plus K fertilizer [39, 49]. Integrated nutrition improved soil nutrient content and increased crop production as an indicator of efficient use of input and resources with positive implications on sustainability.

Some authors claim that the production of cereal crops have stagnated or declined in recent years due to unbalanced and inadequate nutrient application and degradation of the soil organic matter [27]. The decomposition of organic matter releases the nutrients necessary to increase crop yield. Integrated nutrition increased soil organic carbon (SOC) compared to the application of FYM alone (**Figure 17**). A similar result was reported in Malarkodi et al. (2019) and Hejcman and Kunzova (2010) [39, 51]. An increase in SOC indicates organic matter improvement that makes soil condition favorable to increase yield and to sequestrate carbon in crop residues.

The soil pH regulates solubility and availability of nutrients. It increased rapidly during 1958–1998 at integrated nutrition compared to FYM alone by CaO (lime) application (**Figure 18**). Abid et al. (2020) similarly reported that supplementing FYM with NPK fertilizer significantly increased soil pH compared to only FYM [34]. Since 1998, the soil pH was maintained at a desirable level with a slight difference between treatments due to the accumulated effect of lime.

5. Conclusion

Analysis of 62 years of data of the long-term trial confirmed that application of mineral fertilizer N + P + K + Mg as the balanced nutrition and supplementing FYM with mineral fertilizer as the integrated nutrition supports the social, economic, and environmental aspects of sustainable crop production. Any unbalanced nutrition caused by omitting nutrients or applying average quantities of FYM alone resulted in a reduction of crop yield and revenue. It contributed to inefficient use of nutrients and resources, an unstable yield increase, and a depletion of soil fertility with negative implications on sustainability.

Violation of the Law of the Minimum by omitting nutrients decreased crop yield, revenue, SYI, WUE, NUE, PUE, and KUE, respectively by 7–65%, 89–812 $\$ha^{-1}$, 1–22%, 7–63%, 5–23%, 6–49%, and 7–56% compared to the balanced nutrition, because essential functions of the missing nutrients cannot be fulfilled by any other nutrient. Application of FYM alone as organic fertilizer at the local rates in the long-term trial decreased crop yield, revenue, SYI, WUE, NUE, PUE, and KUE, respectively by 44%, 492 $\$ha^{-1}$, 10%, 40%, 33%, 23%, and 24% compared to the integrated nutrition, because nutritional needs of crop were not fully satisfied due to unpredictable availability and the unbalanced ratio of nutrients in the FYM.

Therefore, both the balanced and integrated principles of crop nutrition are the best management strategies to support the positive impacts of technological progress in crop production without depleting the soil fertility. They are important to sustain crop production for future generations while the environment is protected.

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References

[1] Steiner RA, Herdt RW. A global directory of long-term agronomic experiments: Non-European experiments. Vol. l. New York, NY: Rockefeller Foundation; 1993

[2] McRae KB, Ryan DAJ. Design and planning of long-term experiments. Canadian Journal of Plant Science. 1996;**76**:595-602

[3] FAO, Organization of Economic Co-operation and Development (OECD). Food security and nutrition: Challenges for agriculture and the hidden potential of soil [Internet]. A report to the G20 agriculture deputies. 2018. Available from: http://www.fao.org/3/CA0917EN/ca0917en.pdf [Accessed: November 10, 2021]

[4] Roy RN, Finck A, Blair GJ, Tandon HLS. Plant Nutrition for Food Security, a Guide for Integrated Nutrient Management. Rome: FAO Fertilizer and Plant Nutrition Bulletin 16; 2006. p. 17

[5] Peltonen-Sainio P, Jauhiainen L, Laurila IP. Cereal yield trends in northern European conditions: Changes in yield potential and its realization. Field Crops Research. 2008;**4960**:1-6. DOI: 10.1016/j.fcr.2008.07.007

[6] Chander G, Suhas PW, Kanwar L, Pal CK, Mathur TP. Integrated plant genetic and balanced nutrient management enhances crop and water productivity of rainfed production systems in Rajasthan, India. Communications in Soil Science and Plant Analysis. 2013;**44**: 3456-3464

[7] Vyn T. Boosting global corn yields depends on improving nutrient balance [Internet]. 2014. Available from: https://extension.purdue.edu/article/6584 [Accessed: November 10, 2021]

[8] Suhas PW, Chander G, Sahrawat KL, Dixit S, Venkateswarlu B. Improved crop productivity and rural livelihoods through balanced nutrition in the rainfed semiarid tropics. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh and Indian Council of Agricultural Research, New Delhi, India. Resilient Dryland Systems Report number 58. 2013. p. 2

[9] Alley M. M, Vanlauwe B. The role of fertilizers in integrated plant nutrient management [Internet]. IFA and Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture. 2009. Available from: www.fertilizer.org/ifacontent/.../2/file/2009_ifa_role_plant_nutrients.pdf [Accessed: November 10, 2021]

[10] Körschens M. The importance of long-term experiments for soil science and environmental research – A review. Plant Soil Environment. 2006;**52**(Special issue):1-8

[11] Goulding K. Long-term research in the UK: Lessons learned from the Rothamsted classical experiments. In: Report from a Conference on Success Stories of Agricultural Long-Term Experiments. 28-29 May 2007. Uppsala, Sweden: The Royal Swedish Academy of Agriculture and Forestry; 2007. pp. 7-12

[12] Gruhn P, Goletti F, Yudelman M. Integrated Nutrient Management, Soil Fertility, and Sustainable Agriculture: Current Issues and Future Challenges. Vol. 32. Washington DC, USA: International Food Policy Research Institute; 2000. pp. 1-38

[13] International Potash Institute (IPI). Balanced fertilization for sustaining crop

productivity. In: Benbi DK, Brar MS, Bansal SK, editors. Proceedings of the International Symposium; 22-25 November 2006; India. Ludhiana. Horgen, Switzerland: International Potash Institute; 2006. pp. 8-10

[14] Dev G. Balanced fertilizer use increases crop yield and profit in India. Better Crops International. 1998;**12**(2):25-28

[15] Fertilizer Europe (FE). Balanced plant nutrition [Internet]. 2019. Available from: https://www.fertilizerseurope.com/fertilizers-in-europe/balanced-plant-nutrition/ [Accessed: 2021 November 10]

[16] Jones DL, Healey JR. Organic amendments for remediation: Putting waste to good use. Elements. 2010;**6**:369-374

[17] Yara and KTBL. Faustzahlen für die Landwirtschaft. Darmstadt, Germany: KTBL-Schriftenvertrieb im Landwirtschaftsverlag; 2005. p. 263

[18] Kurt GB Lexikon des Agrarraums [Internet]. 2021. Available from: https://www.agrarraum.info/lexikon-g.html#getreide [Accessed: November 10, 2021]

[19] FAO: FAOSTAT. Production crops: data of crop yield and price for Germany [Internet]. 2021. Available from: http://www.fao.org/faostat/en/#data/QCL [Accessed: October 7, 2021]

[20] Yara. Historical data of mineral fertilizer price. "Unpublished data". 2020

[21] Singh PR, Rao SK, Bhaskarrao DUM, Ready MN. Sustainability Index under Different Management; Annual Report. Hydarabad, India: CRIDA; 1990

[22] Qaswar M, Huang J, Ahmed W, Li D, Liu S, Ali S, et al. Long-term green manure rotations improve soil biochemical properties, yield sustainability and nutrient balances in acidic paddy soil under a rice-based cropping system. Agronomy. 2019;**9**:780. DOI: 10.3390/agronomy9120780

[23] Sharmaa A, Sankar GRM, Arorac S, Guptaa V, Singha B, Kumar J, et al. Analyzing rainfall effects for sustainable rainfed maize productivity in foothills of Northwest Himalayas. Field Crops Research. 2013;**145**:96-105

[24] Dobermann A. Nutrient use efficiency measurement and management. In: Papers presented at the IFA international workshop on fertilizer best management practices; 7-9 March 2007; Belgium. Brussels. Paris, France: International Fertilizer Industry Association; 2007. pp. 7-8

[25] Landwirtschafts-kammer Nordrhein-Westfalen (LKNRW): Düngung mit Phosphat, Kali, Magnesium [Internet]. 2015. Available from: https://www.landwirtschaftskammer.de/landwirtschaft/ackerbau/pdf/phosphat-kalium-magnesium-pdf.pdf [Accessed: November 10, 2021]

[26] Allen GG, Begam R, Shrawat A. Sustainable crop production. In: Hudson RJ, editor. Physiology, Biochemistry and Molecular Biology in Animal and Plant Productivity. UK: Encyclopedia of Life Support Systems (EOLSS) and UNESCO, Eolss publishers Co. Ltd; 2010. pp. 294-313

[27] Chopra R, Singh A, Katara P. Nutrient management: Key for sustainable crop production. Popular Kheti. 2014;**2**(2):61-64

[28] Zengin M, Gökmen F, Gezgin S, Cakmak I. Effects of different fertilizers with potassium and magnesium on the

yield and quality of potato. Asian Journal of Chemistry. 2008;**20**(1):663-676

[29] El-Dissoky RA, Al-Kamar FA, Derar RM. Impact of magnesium fertilization on yield and nutrients uptake by maize grown on two different soils. Egyptian Journal of Soil Science. 2017;**57**(4):455-466

[30] Ely EO, Sofyan ET, Sara DS. The effect of NPK+Mg fertilizer application on potassium availability, potassium uptake, and yield of sweet corn (Zea mays Saccharata Sturt) in Inceptisols. International Journal of Energy and Environmental Science. 2020;**5**(3):47-50

[31] Chander G, Suhas PW, Sahrawat KL, Jangawad LS. Balanced plant nutrition enhances rainfed crop yields and water productivity in Jharkhand and Madhya Pradesh states of India. Journal of Tropical Agriculture. 2012;**50**(1-2):24-29

[32] Černý J, Balík J, Kulhánek M, Čásová K, Nedvěd V. Mineral and organic fertilization efficiency in long-term stationary experiments. Plant Soil Environment. 2010;**56**(1):28-36

[33] Dilshad MD, Lone MI, Jilani G, Malik MA, Yousaf M. Integrated plant nutrient management on maize under rainfed condition. Pakistan Journal of Nutrition. 2010;**9**(9):896-901

[34] Abid M, Batool T, Siddique G, Ali S, Binyamin R, Shahid MJ, et al. Integrated nutrient management enhances soil quality and crop productivity in maize-based cropping system. Sustainability. 2020;**12**(23):10214. DOI: 10.3390/su122310214

[35] Bhattacharyya R, Pandey AK, Gopinath KA, Mina BL, Bisht JK, Bhatt JC. Fertilization and crop residue addition impacts on yield sustainability under a rainfed maize–wheat system in the Himalayas. Proceeding of the National Academy of Sciences, India, Section B: Biological Sciences. 2014;**81**(6). DOI: 10.1007/s40011-014-0394-8

[36] Vasuki N, Yogananda SB, Preethu DC, Sudhir K. Impact of Long Term Fertilizer Application on Soil Quality, Crop Productivity, and Sustainability–Two Decades Experience. Bangalore; New Delhi, India: University of Agricultural Sciences; ICAR; 2009. p. 6

[37] Ahrends HE, Siebert S, Rezaei EE, Seidel SJ, Hüging H, Ewert F, et al. Nutrient supply affects the yield stability of major European crops—A 50 year study. Environmental Research Letters. 2021;**16**:014003. DOI: 10.1088/1748-9326/abc849

[38] Ray M, Haldar P, Saha S, Chatterjee S, Adhikary S, Mukhopadhyay SK. Effect of balanced nutrition on productivity, economics and soil fertility of rice (Oryza sativa L.) – greengram [Vigna radiata (L.) Wilczek] cropping system under coastal West Bengal. Journal of Crop and Weed. 2017;**13**(1):89-92

[39] Malarkodi M, Elayarajan M, Arulmozhiselvan K, Gokila B. Long-term impact of fertilizers and manures on crop productivity and soil fertility in an alfisol. The Pharma Innovation Journal. 2019;**8**(7):252-256

[40] Fixen P, Brentrup F, Bruulsema TW, Garcia F, Norton R, Zingore S. Nutrient/fertilizer use efficiency: Measurement, current situation and trends. In: Pay D, Patrick H, Hillel M, Robert M, Dennis W, editors. Managing Water and Fertilizer for Sustainable Agricultural Intensification. Paris, France: IFA; 2015, 2015. pp. 8-39

[41] Kumar P, Dwivedi DK, Bharati V, Tigga A, Singh H, Dwivedi A. Response

of NPK on growth and yield of potato (Solanum tuberosum L.) under calcareous soils of Bihar. International Journal of Current Microbiology App Science. 2021;**10**(02):1956-1961

[42] Wang Y, Wang E, Wang D, Huang S, Ma Y, Smith CJ, et al. Crop productivity and nutrient use efficiency as affected by long-term fertilization in North China Plain. Nutrient Cycle Agroecosystem. 2010;**86**:105-119

[43] Thompson LM, Troeh FR. Soils and soil fertility. 3rd ed. New York: McGraw-Hill; 1973

[44] Bhattacharyya P, Nayak AK, Shahid M, Tripathi R, Mohanty S, Kumar A, et al. Effects of 42-year long-term fertilizer management on soil phosphorus availability, fractionation, adsorption-desorption isotherm and plant uptake in flooded tropical rice. The Crop Journal. 2015;**3**(5):387-395

[45] Zhao S, He P, Qiu S, Jia L, Liu M, Jin J, et al. Long-term effects of potassium fertilization and straw return on soil potassium levels and crop yields in north-central China. Field Crops Research. 2014;**169**:116-122

[46] Sekhon GS, Meelu OP. Organic matter management in relation to crop production in stressed rain fed systems. In: Virmani SM, Katyal JC, Eswaran H, Abrol IP, editors. Stressed Ecosystems and Sustainable Agriculture. New Delhi: Oxford University Press and IBH Publishing; 1994

[47] Aula L, Macnack N, Omara P, Mullock J, Raun W. Effect of fertilizer nitrogen (N) on soil organic carbon, total N and soil pH in long-term continuous winter wheat (*Triticum Aestivum* L.). Communications in Soil Science and Plant Analysis. 2016;**47**(7):863-874

[48] FAO. Guide to efficient plant nutrition management [Internet]. Land and water development division of FAO of the UN. 1998. Available from: www.ftp://ftp.fao.org/agl/agl/docs/gepnm.pdf [Accessed: November 10, 2021]

[49] Mahmood F, Khan I, Ashraf U, Shahzad T, Hussain S, Shahid M, et al. Effects of organic and inorganic manures on maize and their residual impact on soil physico-chemical properties. Journal of Soil Science and Plant Nutrition. 2017;**17**(1):22-32

[50] Baniuniene A, Zekaite V. The effect of mineral and organic fertilizers on potato tuber yield and quality. Agronomijas Vestis (Latvian Journal of Agronomy). 2008;**11**:2002-2006

[51] Hejcman M, Kunzova E. Sustainability of winter wheat production on sandy-loamy Cambisol in the Czech Republic: Results from a long-term fertilizer and crop rotation. Field Crops Research. 2010;**115**:191-199

[52] Dubey R, Sharma RS, Dubey DP. Effect of organic, inorganic and integrated nutrient management on crop productivity, water productivity and soil properties under various rice-based cropping systems in Madhya Pradesh. India. International Journal of Current Microbiology App Science. 2014;**3**(2):381-389