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THE IMPACT OF DIFFERENTIAL FERTILISATION AND IRRIGATION ON THE CONTENT OF POTASSIUM FORM IN LUVISOL

Summary

The present study shows the content of different potassium forms found in lessive soil and was based on a 12-year long field experiment. In this work the following conditions were used: differential N fertilization and differential irrigation (fields were either left with no water or irrigated). The soil samples were collected from three different depths that matched genotypes of lessive soil: 0-30, 30-60 and 60-90 cm. We have mapped the following potassium forms: active (K-$CaCl_2$), bioavailable Enger-Riehm (K-Dl), exchangeable (K-CH_3COONH_4), fixed (K-HCl) and non-exchangeable (K-HNO_3). We observed that with the increased concentrations of N fertilization, there was a reduction in the content of potassium forms, in particular when fields were irrigated. Moreover, in majority of cases, there were fewer potassium forms on irrigated fields (in particular on 0-30 cm).

***Key words**: Luvisol, nitrogen fertilisation, irrigation, potassium forms, potassium fixation, long-term experiments*

ZAWARTOŚĆ FORM POTASU W GLEBIE PŁOWEJ W WARUNKACH ZRÓŻNICOWANEGO NAWOŻENIA AZOTOWEGO I NAWADNIANIA

Streszczenie

W pracy przedstawiono wyniki badań dotyczące ilości form potasu w glebie płowej. Badania prowadzono na próbkach glebowych pobranych z długoletniego doświadczenia polowego (dwunastoletniego) założonego na glebie płowej. Czynnikami doświadczenia były: zróżnicowane nawożenie azotowe oraz reżim wodny (poletka deszczowane i nie deszczowane). Próbki do badań pobrano z trzech głębokości 0-30, 30-60 i 60-90 cm, które odpowiadały trzem kolejnym poziomom genetycznym gleby płowej. W pracy oznaczono następujące formy potasu: aktywny (K-$CaCl_2$), przyswajalny Egnera-Riehma (K-Dl), wymienny (K-CH_3COONH_4), uwsteczniony (K-HCl) oraz zapasowy (K-HNO_3). Zastosowane w doświadczeniu czynniki miały w wielu przypadkach istotny wpływ na zróżnicowanie ilości analizowanych form potasu. Wraz ze wzrostem zastosowanej dawki nawożenia azotowego malała zawartość analizowanych form potasu, szczególnie na obiektach deszczowanych. Na obiektach deszczowanych zaobserwowano także w większości przypadków mniejszą zawartość analizowanych form potasu szczególnie w poziomie 0-30 cm.

***Key words**: gleba płowa, nawożenie azotowe, deszczowanie, formy K, fiksacja potasu, doświadczenie wieloletnie*

1. Introduction

The overall content of potassium in soil ranges between 0,01 and 4% with a median of approximately 1% and is dependent on the origin of the soil [3,32]. The forms of potassium are determined using Egner-Riehm (ER) method [7, 9, 25]. Using this approach enables determination of six forms of potassium: soil solution K, active K (extracted with $CaCl_2$), exchangeable K, fixed K (extracted with cold HCl), non-exchangeable K (extracted with hot HNO_3) and total K found in crystal lattice of silicate minerals [25]. Many authors claim that the excess potassium (unutilized by plants) is prone to leaching and/or unchangeably bound by the soil complex [21, 24]. The above forms of potassium can be characterised based on their chemical properties and are differently absorbed by plants. Fertilization has the largest impact on the content of potassium being absorbed by plants from soil [4, 6, 13, 28]. There are different factors controlling the efficiency of fertilization with potassium and its absorption by plants. These are the soil type, the water absorption capacity, the plants composition and diversity and the level of N and K fertilization [29]. Potassium found in sandy soils is easily eluted [2, 5, 12, 20, 15, 21]. In this context, Fotyma at al. [9] show that there is a positive correlation between exchangeable potassium and the concentration of K eluted from sandy soils. Moreover, Pal et al. [19] observed that soils classified as "light and very light" that have low content of potassium, are more efficiently fertilised with small but multiple doses of potassium, especially during the vegetative period [19]. This is in contrast to clayey soils that can be fertilised with single doses of potassium due to their higher abilities to retain the solution. However, there is a possibility that potassium may be retained between layers of clay minerals [18]. Potassium fertilisation in doses that are higher than the actual plants' requirements may lead to an increase in potassium forms that are easily available to plants and hence enhance the vegetation in the coming years [17]. According to published studies [1, 14, 26, 29], potassium that is not absorbed by plants usually undergoes interchangeable sorption, a process that depends on pH, quantity and quality of clay minerals and the extent of potassium saturation by sorption complex. Therefore, in order to maximise the effectiveness of potassium fertilisers, they must be used at the correct time of the year and using appropriate techniques [33].

Accordingly, the aim of the study was the determination of the content of different potassium forms in chosen genetic horizon of soils under differential N fertilisation and irrigation.

2. Materials and methods

Field experiments were carried out on lessive soil classified as very good and good rye complex (bonite class IVa and IVb) in Experimental Station in Złotniki that is a part of the Poznan University of Life Sciences (Figure 1). The experimental fields are situated at Poznan morainic plateau (within Poznań Plain; its north part belongs to Szamotuły Plain and Poznań hills). The soil is composed of morainic clay that originates from Baltic glaciation. The upper layers are formed by sandy ice wedges 50-80 cm deep that gradually disappear (at 4-5 meters) [11]. The study was set up in 1996 and was based on static crop rotation experiments. During the four-year crop rotation the following plants were cultivated: sugar beets – spring triticale – pea – winter wheat. The study had two experimental variables i.e. irrigation and fertilization. In a randomized complete block layout with split units was repeated four replication. The experimental soils were non-irrigated or irrigated. In the latter case: additional irrigation was used when the humidity of the soil (within 0-30 cm) was below 70%. We used four N fertilisation modes:

- N0 – control – no N fertilisation
- N1 – sugar beets – 80, spring triticale – 50, pea – 30, winter wheat – 50 kg/ha
- N2 - sugar beets – 160, spring triticale – 100, pea – 60, winter wheat – 100 kg/ha
- N3 - sugar beets – 240, spring triticale – 150, pea – 90, winter wheat – 150 kg/ha.

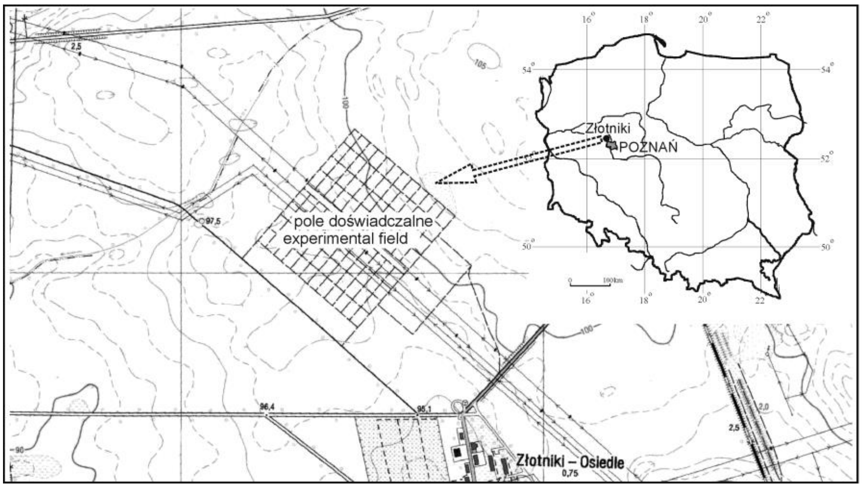
Within the crop rotations were used fertilisation with P and K was used according to the procedures by IUNG-PIB Puławy [23]. When additional irrigation was required, 30-270 mm water was used depending on the plant diversity and year.

The soil samples for laboratory experiments were collected in autumn, after sugar beets were harvested in soil profile from three layers that corresponded to three consecutive genotypic levels (humus – 0-30 cm Ap, eluvial 30-60 cm Et and enriched 60-90 cm Bt). From 72 experimental plots was collected 288 soil samples. The samples were dried, minced and sifted through a 2 mm sieve. Forms of potassium were extracted from air-dried soil with single extraction methods [25] and are shown in Table 1.

Data was analysed using Statistica 12 - variance analysis and uniform groups were designated using Turkey test (significance of α=0.05).

3. Results and discussion

Table 2 shows the texture of soil samples. The soil samples were classified based on their texture according to Polish Soil Society as loamy sands embedded moderately deep within light loam. The content of clay, which has the biggest impact on the interchangeable and non-interchangeable sorption of potassium, ranged between 1-4% in the upper layers (Ap), 1-5% in the layers of 30-60 cm deep (Et) and 16-24% in Bt layers.



Source: own work / Źródło: opracowanie własne

Fig. 1. The location of the object of investigations
Rys. 1. Lokalizacja obiektu badań

Table 1. Methods used to obtain different forms of potassium
Tab. 1. Metody oznaczania analizowanych form potasu

K forms	Chemical reagent	Symbol	Method of extraction
Active	0,01 mol·dm^{-3} $CaCl_2$	K - $CaCl_2$	2 g soil + 100 cm^3 0,01 mol·dm^3 $CaCl_2$ (1:50) → shaking for 1,5 h → filtering → K determination with Varian FS 220
Exchangeable	1 mol·dm^{-3} NH_4OAc pH 7,0	K - CH_3COONH_4	2 g soil + 50 cm^3 CH_3COONH_4 (1:25) → shaking for 1,5 h, centrifuging for 10 min at 3600 rpm → residuum treated with 50 cm^3 CH_3COONH_4 → filtering → K determination with Varian FS 220
Fixed	2 mol·dm^{-3} HCl	K - HCl	2 g soil + 100 cm^3 2 mol· dm^{-3} HCl → shaking for 2 h → filtering → K determination with Varian FS 220
Non-exchangeable	1 mol·dm^{-3} HNO_3	K - HNO_3	2 g soil + 100 cm^3 1 mol· dm^{-3} HNO_3 → extraction at 80°C → shaking → filtering → K determination with Varian FS 220
Bioavailable (Egner-Riehm)	$(C_2H_2OHCOO)_2Ca$ + HCl pH 3,6	K - Dl	2 g soil + 100 cm^3 acidified Ca lactate (DL - Egner-Riehm soln.) → shaking for 1,5 h → filtering → K determination with Varian FS 220

Source: own work / Źródło: opracowanie własne

Table 2. Texture of soil
Tab. 2. Skład granulometryczny gleby

Soil horizon	Depth cm		Fraction (%)			Textural group	
			sand 2,0-0,05 mm	silt 0,05-0,002 mm	clay <0,002 mm	PSS 2008[1]	FAO/USDA[2]
A	0-30	average	82	16	2	Ls	Ls
		range	79-86	11-20	1-4	-	-
Et	30-60	average	84	14	2	Ls	Ls
		range	77-95	5-19	1-5	-	-
Bt	60-90	average	63	17	20	Ls	Sl
		range	55-69	14-22	16-24	-	-
C	>90	average	64	18	18	L	Sl
		range	59-67	15-23	14-22	-	-

[1] – according Polish Soil Society; [2] – according United State Department of Agronomy

Source: own work / Źródło: opracowanie własne

Active potassium extracted with 0,01 mol · dm^{-3} calcium chloride is described as the form of potassium that is loosely associated with sorption complex. The content of active potassium in collected soil samples was from 74,6 to 135,4 mg K · kg^{-1} in 0-30 cm layer – from 51,1 to 114,3 mg K · kg^{-1} in 30-60 cm layer and from 92,9 to 132,6 mg K · kg^{-1} in 60-90 cm layer.

The average values for the content of active potassium are shown in Tables 3 and 4. Here we show that irrigation had a major impact on the content of active potassium in non-fertilised soil compared to irrigated and fertilised soil. The control soil samples collected from experimental fields where no irrigation and no fertilisation was used showed significantly higher content of active potassium in layers of 0-30 cm and 60-90 cm but significantly lower content of active potassium in 30-60 cm layer. In contrast, irrigation had no impact on the active potassium content when 80 kg N·ha^{-1} (N1) was used in all tested samples. Similar results were obtained when 160 kg N·ha^{-1} (N2) was used but only in 60-90 cm layer. The soil samples collected from non-irrigated experimental fields where additional fertilisation of 160 kg N·ha^{-1} (N2) was used showed significantly higher content of active potassium in layers of 0-30 cm and 30-60 cm. Moreover, similar results were obtained from non-irrigated and fertilised with 240 kg N · ha^{-1} (N3) soil samples collected from all different layers. To summarise, combined fertilisation and irrigation led to significant changes in active potassium content in all layers in contrast to differential content of active potassium in 0-30 cm layer where fertilisation but no irrigation was used.

The highest concentration of active potassium - 90,1 mg K · kg^{-1} was found in the upper layer of irrigated soil where N2 fertilisation was used, whereas the lowest concentration of active potassium – 74,6 mg K · kg^{-1} was found in the soil fertilised with 240 kg N · ha^{-1} (N3). Furthermore, we observed that soil samples collected from 0-30 cm had reduced content of active potassium, which correlated with the increase in N fertilisation. The lowest active potassium content – 51,1 mg K · kg^{-1} was found in soil samples collected from irrigated and fertilised with 240 kg N · ha^{-1} (N3) experimental fields. In contrast the highest active potassium content – 92,9 mg K · kg^{-1} was found in soil samples from control experimental fields fertilised with 106,2 kg N · ha^{-1} (N0). In the layer of 60-90 cm the lowest content of potassium – 92,9 mg K · kg^{-1} was observed in soil samples where no fertilisation was used and the highest – 132,6 mg K · kg^{-1} where 80 kg N · ha^{-1} (N1) was used. Differential fertilisation was found to have an impact on the content of active potassium in samples from non-irrigated soil from layers of 0-30 cm and 30-60 cm. In 0-30 cm layer, there was a reduction in potassium content to 93,2 mg K · kg^{-1} and 95,5 mg K · kg^{-1} in soil samples collected from experimental fields that were either fertilised with 80 kg N · ha^{-1} (N3) or non-fertilised, respectively. In the same layer, the highest potassium content of 135,4 mg K · kg^{-1} was found in samples where 160 kg N · ha^{-1} (N2) was used. In 30-60 cm layer of non-irrigated soil, the lowest potassium content of 77,1 mg K · kg^{-1} was observed where fertilisation in dose of 240 kg N ·ha^{-1} (N3) was applied, and the highest – 114,3 mg K · kg^{-1} where 160 kg N · ha^{-1} (N2) was used. In 60-90 cm layer, there were no significant changes in active potassium content in all tested doses of N fertilisation.

The average percentage share of active potassium content compared to non-exchangeable potassium, which is extracted with 1 mol · dm^{-3} hot HNO_3 ranged between 12 and 20% in 0-30 cm, whereas the layer of 30-60 cm had a lower percentage share of active potassium and ranged between 8-17%. The lowest percentage share of active potassium was found in 60-90 cm and ranged between 8-10%.

Table 3. The influence of water conditions on the average content of active potassium in soil samples from plots with different N fertilization dose (mg K·kg^{-1})
Tab. 3. Wpływ wariantu wodnego na zawartość potasu aktywnego w próbkach glebowych pobranych z poletek po zastosowaniu zróżnicowanego nawożenia azotowego (mg K·kg^{-1})

Water conditions / Nitrogen dose	Depth in cm		
	0-30 (Ap)	30-60 (Et)	60-90 (Bt)
N0			
Irrigated	85,7a	106,2b	92,9a
Non-irrigated	95,5b	94,2a	111,9b
N1			
Irrigated	82,1a	103,1a	132,6a
Non-irrigated	93,2a	105,6a	126,6a
N2			
Irrigated	90,1a	93,8a	104,8a
Non-irrigated	135,4b	114,3b	124,0a
N3			
irrigated	74,6a	51,1a	108,5a
non-irrigated	108,3b	77,1b	127,6b

differences between medians marked by the same letters are not significant

Source: own work / Źródło: opracowanie własne

Table 4. The influence of dose nitrogen fertilization on the average content of active potassium in analysed soil samples (mg K·kg^{-1})

Tab. 4. Wpływ zróżnicowanego nawożenia azotowego na zawartość potasu aktywnego w analizowanych próbkach glebowych (mg K·kg^{-1})

Nitrogen dose/ Download depth		Depth in cm		
		0-30 (Ap)	30-60 (Et)	60-90 (Bt)
Irrigated	N0	85,7b	106,2c	92,9a
	N1	82,1ab	103,1bc	132,6c
	N2	90,1b	93,8b	104,8ab
	N3	74,6a	51,1a	108,5b
non-irrigated	N0	95,5a	94,2ab	111,9a
	N1	93,2a	105,6bc	126,6a
	N2	135,4c	114,3c	124,0a
	N3	108,3b	77,1a	127,6a

differences between medians marked by the same letters are not significant

Source: own work / Źródło: opracowanie własne

Bioavailable potassium extracted using Egner-Rhiem method is a mixture of potassium forms that are found in soil solution and that are interchangeably bound with soil sorption complex. We found that this form of potassium was slightly more abundant compared to active potassium. The content of bioavailable potassium in collected soil samples was from 99,4 to 135,9 mg K · kg^{-1} in a layer from 0-30 cm, from 57,7 to 142,0 mg K · kg^{-1} in a layer from 30-60 cm and from 120,5 to 166,3 mg K · kg^{-1} in a layer from 60-90 cm.

The results for the content of bioavailable potassium are summarised in Tables 5 and 6. The variance analysis showed that the usage of irrigation resulted in statistically significant reduction in the content of bioavailable potassium. There was a higher content of K-DL in soil samples collected from the top layer (Ap) of non-irrigated experimental fields that were either fertilised with 160 kg N · ha^{-1} (N2) and 240 kg N · ha^{-1} (N3) or unfertilised compared to irrigated soil samples. Similarly, the content of bioavailable potassium was significantly higher in soil samples collected from 30-60 cm (Et) layer that were non-irrigated and fertilised with either N1, N2 or N3 doses. Same results were observed in soil samples collected from 60-90 cm layer from experimental fields marked as control (N0) or fertilised with 240 kg N · ha^{-1} (N3). There was a significantly higher content of bioavailable potassium content in soil samples collected from 30-60 cm layer of irrigated control (N0) field experiments. There were no statistically significant differences on the content of bioactive potassium in samples from the upper layer of soil where increased doses of fertilisation were used (both irrigated and non-irrigated). In contrast, in 30-60 cm layer of irrigated soil, the content of bioactive potassium was strongly dependent on the different doses of N fertilisation. The findings that increased doses of N fertilisation lead to a decrease in the content of bioavailable potassium are in line with published data from Murawska [16] and Stepien and Mercik [27]. There was a significant impact on the differential doses of N fertilisation on the content of bioavailable potassium in soil samples collected from 30-60 cm (Et) of non-irrigated experimental fields. The highest content of bioavailable potassium – 142,0 mg K · kg^{-1} was registered in samples from control field experiments. In contrast, there was a reduction of bioavailable form of potassium in samples collected from the same layer but where N fertilisation of 80 and 160 kg N · ha^{-1} were used. The lowest content of bioavailable potassium – 57,2 mg K · kg^{-1} was found in soil samples collected from the experimental fields treated with 240 kg N · ha^{-1}. There were no statistically significant changes in the content of K-DL in non-irrigated soil samples collected from 30-60 cm layer. In contrast, we found that N fertilisation led to different content of bioavailable potassium collected from 60-90 cm layer in both irrigated and non-irrigated samples. The lowest content of bioavailable potassium – 120,5 mg K · kg^{-1} was found in irrigated and non-fertilised soil samples. Significantly higher content of bioavailable potassium (K-DL) was observed in samples fertilised with 160 kg N · ha^{-1} and 240 kg N · ha^{-1}. The highest K-DL concentration of 153,0 mg K · kg^{-1} was found in samples that were fertilised with 80 kg N · ha^{-1}. Within the non-irrigated samples, we observed that different N fertilisation had an impact on the content of bioavailable potassium. The lowest content of bioavailable potassium – 129,3 mg K · kg^{-1} was found in control soil samples. However, the application of 240 kg N · ha^{-1} fertilisation resulted in statistically significant increase in K-DL content compared to control samples – 166 mg K · kg^{-1}. The average percentage share of bioavailable potassium content compared to non-exchangeable potassium, ranged between 16 and 21% in 0-30 cm (Figure 2). The layer of 30-60 cm had a lower percentage share of bioavailable potassium compared K-HNO_3 and ranged between 9-17%. The lowest percentage share of bioavailable potassium was found in 60-90 cm and ranged between 10-12%. We observed that there was a high positive correlation between bioavailable form of potassium and active potassium – R=0,82 as well as exchangeable potassium – R=0,78 and also K-KCl – R=0,88. These observations are in line with findings from Murawska [16] and Fotyma at al [9].

Table 5 The influence of water conditions on the average content of bioavailable potassium measured by Egner-Riehm method (K-DL) in soil samples from plots with different N fertilization dose (mg K·kg^{-1})

Tab. 5. Wpływ wariantu wodnego na zawartość potasu przyswajalnego (Egnera-Riehma DL) w próbkach glebowych pobranych z poletek po zastosowaniu zróżnicowanego nawożenia azotowego (mg K·kg^{-1})

Water conditions / Dose of nitrogen	Depth in cm		
	0-30 (Ap)	30-60 (Et)	60-90 (Bt)
N0			
Irrigated	105,1a	142,0b	120,5a
Non-irrigated	115,4b	96,8a	129,3b
N1			
Irrigated	104,7a	91,8a	153,0a
Non-irrigated	122,9a	117,4b	140,3a
N2			
Irrigated	105,3a	76,7a	140,5a
Non-irrigated	135,9b	110,3b	154,4a
N3			
Irrigated	99,4a	57,2a	137,3a
Non-irrigated	127,5b	102,0b	166,3b

differences between medians marked by the same letters are not significant

Source: own work / Źródło: opracowanie własne

Table 6. The influence of dose N fertilization on the average content of bioavailable potassium measured by Egner-Riehm method (K-DL) in analysed soil samples (mg K·kg^{-1})

Tab. 6. Wpływ zróżnicowanego nawożenia azotowego na zawartość potasu przyswajalnego (Egnera-Riehma DL) w analizowanych próbkach glebowych (mg K·kg^{-1})

Nitrogen rate / Download depth		Depth in cm		
		0-30 (Ap)	30-60 (Et)	60-90 (Bt)
Irrigated	N0	105,1a	142,0c	120,5a
	N1	104,7a	91,8b	153,0c
	N2	105,3a	76,7b	140,5bc
	N3	99,4a	57,2a	137,3b
Non-irrigated	N0	115,4a	96,8a	129,3a
	N1	122,9a	117,4a	140,3ab
	N2	135,9a	110,3a	154,4ab
	N3	127,5a	102,0a	166,3b

differences between medians marked by the same letters are not significant

Source: own work / Źródło: opracowanie własne

Exchangeable form of potassium is a mixture of potassium forms that are loosely bound to sorption complex and yet undefined form. The results for the content of exchangeable potassium are summarised in Tables 7 and 8. The statistical analysis showed that the use of irrigation as well as some doses of N fertilisation had a significant impact on the content of exchangeable potassium. Similarly to the above data, irrigation led to a significant reduction of the content of exchangeable potassium in upper layers (0-30 cm) from control and fertilised with 160 kg N · ha^{-1} and 240 kg N · ha^{-1} experimental fields. Furthermore, we also found that irrigation led to significant changes in content of exchangeable potassium in 30-60 cm layer, for example where soil samples were treated with 80 kg N · ha^{-1}, 160 kg N · ha^{-1} and 240 kg N · ha^{-1} there was a reduction in its content. Fertilisation with 240 kg N · ha^{-1} had a significant impact on potassium content in 60-90 cm layer (Bt). In contrast there was no significant impact on exchangeable potassium content in either irrigated or non-irrigated soil samples fertilised with 80 kg N · ha^{-1} collected from 0-30 cm layer, unfertilised Et layer, Bt layer from fertilised with 80 and 60 kg N · ha^{-1}. The content of exchangeable potassium collected from Ap level was different between irrigated soil samples fertilised with 240 kg N · ha^{-1} – 86,9 mg K · kg^{-1} and non-fertilised - 107,8 mg K · kg^{-1} (Table 8). Soil samples that were collected from non-irrigated experimental fields showed no differences in exchangeable potassium content after different doses of N fertilisation and similar was observed in Et level. However, when irrigated, soil samples from level Et showed differential content of exchangeable potassium depending on N fertilisation. The lowest content of exchangeable potassium – 48,4 mg K · kg^{-1} was found in soil samples collected from the experimental fields treated with 240 kg N · ha^{-1}, whereas the highest – 104,8 mg K · kg^{-1} from control fields. N fertilisation led to different content of exchangeable potassium in samples collected from 60-90 cm layer in both irrigated and non-irrigated samples. The lowest content of exchangeable potassium – 105,9 mg K · kg^{-1} was found in irrigated and fertilised soil samples with 160 kg N · ha^{-1}. In contrast, the highest concentration of exchangeable potassium – 168,6 mg K · kg^{-1} was found in control samples. Where no irrigation was used, the lowest content of potassium was found in control samples – 104,6 mg K · kg^{-1} and the highest – 158,4 mg K · kg^{-1} in samples fertilised with 240 kg N · ha^{-1}.

The average percentage share of exchangeable potassium content compared to non-exchangeable potassium, ranged between 14 and 20% in 0-30 cm. The layer of 30-60 cm had a lower percentage share of exchangeable potassium compared K-HNO_3 and ranged between 8-19%. The lowest percentage share of exchangeable potassium was found in 60-90 cm and ranged between 9-14%. We noticed that there was a strong correlation between exchangeable form of potassium and the above mentioned. Murawska [15] also observed strong correlation between bioavailable and exchangeable potassium with R=0.69.

Table 7 The influence of water conditions on the average content of exchangeable potassium (K-CH_3COONH_4) in soil samples from plots with different N fertilization dose (mg K·kg^{-1})

Tab. 7. Wpływ wariantu wodnego na zawartość potasu wymiennego (K-CH_3COONH_4) w próbkach glebowych pobranych z poletek po zastosowaniu zróżnicowanego nawożenia azotowego (mg K·kg^{-1})

Water conditions / Dose of nitrogen	Depth in cm		
	0-30 (Ap)	30-60 (Et)	60-90 (Bt)
N0			
Irrigated	99,8a	104,8a	168,6b
Non-irrigated	136,0b	99,5a	104,6a
N1			
Irrigated	100,3a	67,8a	152,7a
Non-irrigated	134,7a	100,2b	145,3a
N2			
Irrigated	107,8a	63,6a	105,9a
Non-irrigated	135,1b	96,4b	127,9a
N3			
Irrigated	86,9a	48,4a	130,7a
Non-irrigated	121,0b	124,4b	158,4b

differences between medians marked by the same letters are not significant

Source: own work / Źródło: opracowanie własne

Table 8. The influence of dose N fertilization on the average content of exchangeable potassium (K-CH_3COONH_4) in analysed soil samples (mg K·kg^{-1})

Tab. 8. Wpływ zróżnicowanego nawożenia azotowego na zawartość potasu wymiennego (K-CH_3COONH_4) w analizowanych próbkach glebowych (mg K·kg^{-1})

Nitrogen dose / Download depth		Depth in cm		
		0-30 (Ap)	30-60 (Et)	60-90 (Bt)
Irrigated	N0	99,8ab	104,8b	168,6c
	N1	100,3ab	67,8a	152,7c
	N2	107,8b	63,6a	105,9a
	N3	86,9a	48,4a	130,7b
Non-irrigated	N0	136,0a	99,5a	104,6a
	N1	134,7a	100,2a	145,3b
	N2	135,1a	96,4a	127,9ab
	N3	121,0a	124,4a	158,4b

differences between medians marked by the same letters are not significant

Source: own work / Źródło: opracowanie własne

Stepien at al [28] suggested that the content of exchangeable potassium in soil could serve as an indicator for how much potassium is available to plants. They proposed that exchangeable potassium is relatively easy accessible to plants and is less exposed to washout compared to the fraction of potassium occuring in soil water.

Fixed potassium is extracted with 2 mol · dm^{-3} with hydrochloric acid [23]. The content of fixed potassium in collected soil samples was as follow:

- layer from 0-30 cm – from 170,1 to 241,1 mg K · kg^{-1}
- layer from 30-60 cm - from 138,9 to 241,1 mg K · kg^{-1}
- layer from 60-90 cm - from 242,2 to 313,4 mg K · kg^{-1}.

The results for the content of fixed potassium are summarised in Tables 9 and 10. The amount of fixed potassium was higher than the content of other forms of potassium that were previously discussed. The statistical analysis showed that irrigation had a significant impact on reduction of fixed potassium in Ap level in soil fertilised with 160 and 240 kg N · ha^{-1}. The content of fixed potassium from in samples collected from control fields and fields fertilised with 160 kg N · ha^{-1} was significantly lower than in samples from irrigated fields. However, there was no statistically significant impact of irrigation on reduction of fixed potassium content in samples collected from 30-60 cm fertilised with 80 and 240 kg N · ha^{-1} and from 60-90 cm fertilised with all doses of N. The content of fixed potassium was not affected by different doses of N fertilisation in top layer of irrigated and non-irrigated soil. In contrast, the statistical analysis showed that different doses on N fertilisation had a significant impact on fixed potassium content in irrigated soil collected from 30-60 cm layer. The highest amount of fixed potassium – 241,1 mg K · kg^{-1} was found in control samples, whereas significantly less potassium – 174,57 mg K · kg^{-1} was found where 80 kg N · ha^{-1} was used. The lowest content of potassium of 138,87 mg K · kg^{-1} was observed in samples where 160 kg N · ha^{-1} was applied. There were no statistical differences in K-HCl after different N fertilisation in irrigated or non-irrigated soil within 60-90 cm layer.

Table 9. The influence of water conditions on the average content of fixed potassium (K-HCl) in soil samples from plots with different N fertilization dose (mg K·kg^{-1})

Tab. 9. Wpływ wariantu wodnego na zawartość potasu uwstecznionego (K-HCl)) w próbkach glebowych pobranych z poletek po zastosowaniu zróżnicowanego nawożenia azotowego (mg K·kg^{-1})

Water conditions / Dose of nitrogen	Depth in cm		
	0-30 (Ap)	30-60 (Et)	60-90 (Bt)
N0			
Irrigated	176,8a	241,1b	277,2a
Non-irrigated	235,5a	185,8a	313,4a
N1			
Irrigated	200,7a	174,6a	284,0a
Non-irrigated	241,1a	217,2a	289,0a
N2			
Irrigated	188,5a	138,9a	242,2a
Non-irrigated	221,6b	222,3b	313,1a
N3			
Irrigated	170,1a	143,2a	272,2a
Non-irrigated	213,8b	199,6a	301,4a

differences between medians marked by the same letters are not significant

Source: own work / Źródło: opracowanie własne

Table 10. The influence of dose N fertilization on the average content of fixed potassium (K-HCl) in analysed soil samples (mg K·kg^{-1})

Tab. 10. Wpływ zróżnicowanego nawożenia azotowego na zawartość potasu uwstecznionego (K-HCl) w analizowanych próbkach glebowych (mg K·kg^{-1})

Nitrogen dose / Download depth		Depth in cm		
		0-30 (Ap)	30-60 (Et)	60-90 (Bt)
Irrigated	N0	176,8a	241,1c	277,2a
	N1	200,7a	174,6b	284,0a
	N2	188,5a	138,9a	242,2a
	N3	170,1a	143,2a	272,2a
Non-irrigated	N0	235,5a	185,8a	313,4a
	N1	241,1a	217,2a	289,0a
	N2	221,6a	222,3a	313,1a
	N3	213,8a	199,6a	301,4a

differences between medians marked by the same letters are not significant

Source: own work / Źródło: opracowanie własne

The highest content of fixed potassium was observed in level Bt (60-90 cm).

The average percentage share of fixed potassium content compared to non-exchangeablenon-exchangeable potassium, ranged between 27 and 35% in 0-30 cm. The lowest percentage share of fixed potassium was found in 60-90 cm and ranged between 19-26%.

Non-exchangeable form of potassium was the most abundant amongst all tested forms. The results for the content of non-exchangeable potassium are summarised in Tables 11 and 12. We observed a reduction of non-exchangeable potassium content in samples collected from irrigated soil, however the samples from Ap level for control and fertilised samples with 80 and 240 kg N · ha^{-1} did not reach statistical significance. There was a significant increase in content of non-exchangeable potassium in non-irrigated samples fertilised with 160 kg N · ha^{-1}. Furthermore, higher content of non-exchangeable potassium was found in irrigated, non-fertilised soil samples from 30-60 cm layer. In all other cases, the impact of irrigation on content of potassium did not reach statistical significance. Similarly, irrigation had no impact on non-exchangeable potassium content in non-fertilised and fertilised with 160 and 240 kg N · ha^{-1} within 60-90 cm. However, variance analysis showed that irrigation and fertilisation with 80 kg N · ha^{-1} led to statistically significant increase in potassium content.

There were no significant differences from non-exchangeable potassium content in irrigated or non-irrigated soil samples collected from arable layer due to differential fertilisation. N fertilisation significantly influenced the content of potassium in irrigated soil from 30-60 cm. Non-irrigated and non-fertilised soil had the highest content of non-exchangeable potassium of 872,6 mg K · kg^{-1}. The remaining doses of N fertilisation had no impact on potassium content in irrigated soil. The statistical analysis did not show any differences in potassium content in non-irrigated soil fertilised with different N doses in 30-60 cm layer. Similar results were obtained for irrigated and non-irrigated soil samples collected from 60-90 cm. However, there was a trend towards higher content of non-exchangeable potassium in deeper layers of soil.

Table 11. The influence of water conditions on the average content of non-exchangeable potassium (K- HNO_3) in soil samples from plots with different N fertilization dose (mg K·kg^{-1})
Tab. 11. Wpływ wariantu wodnego na zawartość potasu zapasowego (K- HNO_3)w próbkach glebowych pobranych z poletek po zastosowaniu zróżnicowanego nawożenia azotowego (mg K·kg^{-1})

Water conditions / Dose of nitrogen	Depth in cm		
	0-30 (Ap)	30-60 (Et)	60-90 (Bt)
N0			
Irrigated	634,4a	872,6b	1239,1a
Non-irrigated	691,0a	727,8a	1169,2a
N1			
Irrigated	596,9a	697,0a	1509,6b
Non-irrigated	659,5a	799,9a	1261,7a
N2			
Irrigated	593,1a	587,6a	1254,9a
Non-irrigated	638,1b	639,2a	1145,7a
N3			
Irrigated	626,1a	636,4a	1468,3a
Non-irrigated	684,9a	632,3a	1327,8a

differences between medians marked by the same letters are not significant

Source: own work / Źródło: opracowanie własne

Table 12. The influence of dose fertilization on the average content of non-exchangeable potassium (K- HNO_3) in analysed soil samples (mg K·kg^{-1})
Tab. 12. Wpływ zróżnicowanego nawożenia azotowego na zawartość potasu zapasowego (K- HNO_3) w analizowanych próbkach glebowych (mg K·kg^{-1})

Nitrogen rate / Download depth		Depth in cm		
		0-30 (Ap)	30-60 (Et)	60-90 (Bt)
Irrigated	N0	634,4a	872,6b	1239,1a
	N1	596,9a	697,0a	1509,6a
	N2	593,1a	587,6a	1254,9a
	N3	626,1a	636,4a	1468,3a
Non-irrigated	N0	691,0a	727,8a	1169,2a
	N1	659,5a	799,9a	1261,7a
	N2	638,1a	639,2a	1145,7a
	N3	684,9a	632,3a	1327,8a

differences between medians marked by the same letters are not significant

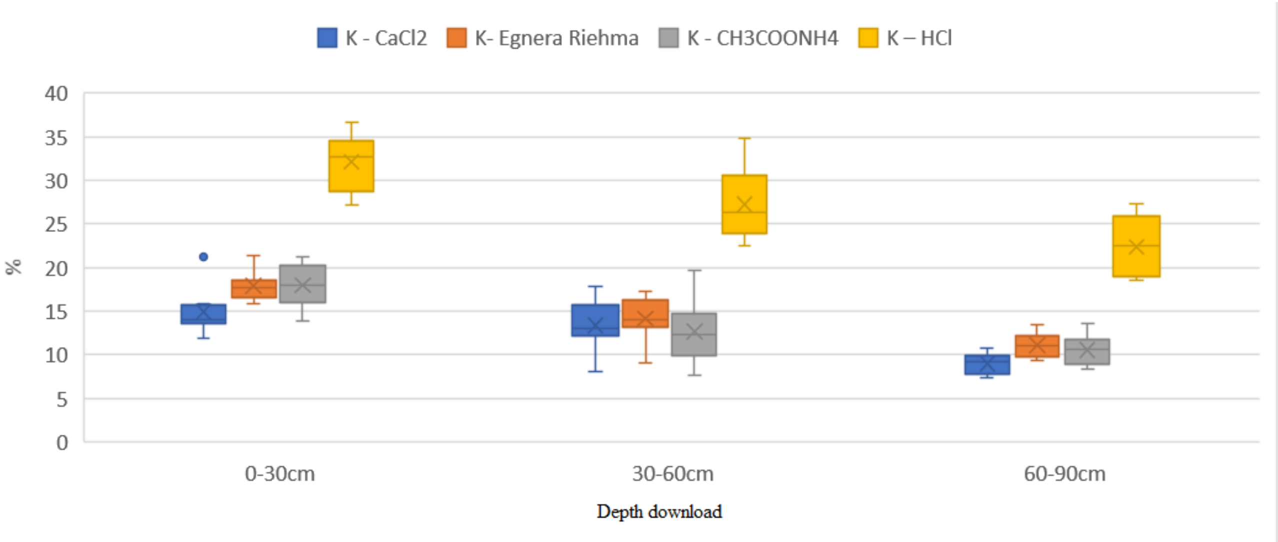
Source: own work / Źródło: opracowanie własne

The forms of potassium that were examined were highly correlated with each other with variance coefficient ranging between 0,57 and 0,88. The R2 values are shown in Table 13. The strong correlation between bioavailable and active potassium was previously discussed by Fotyma et al [9] and Spychalski at al. [22].

Table 13. Correlations coefficient between analysed forms of potassium
Tab. 13. Współczynniki korelacji pomiędzy analizowanymi formami potasu

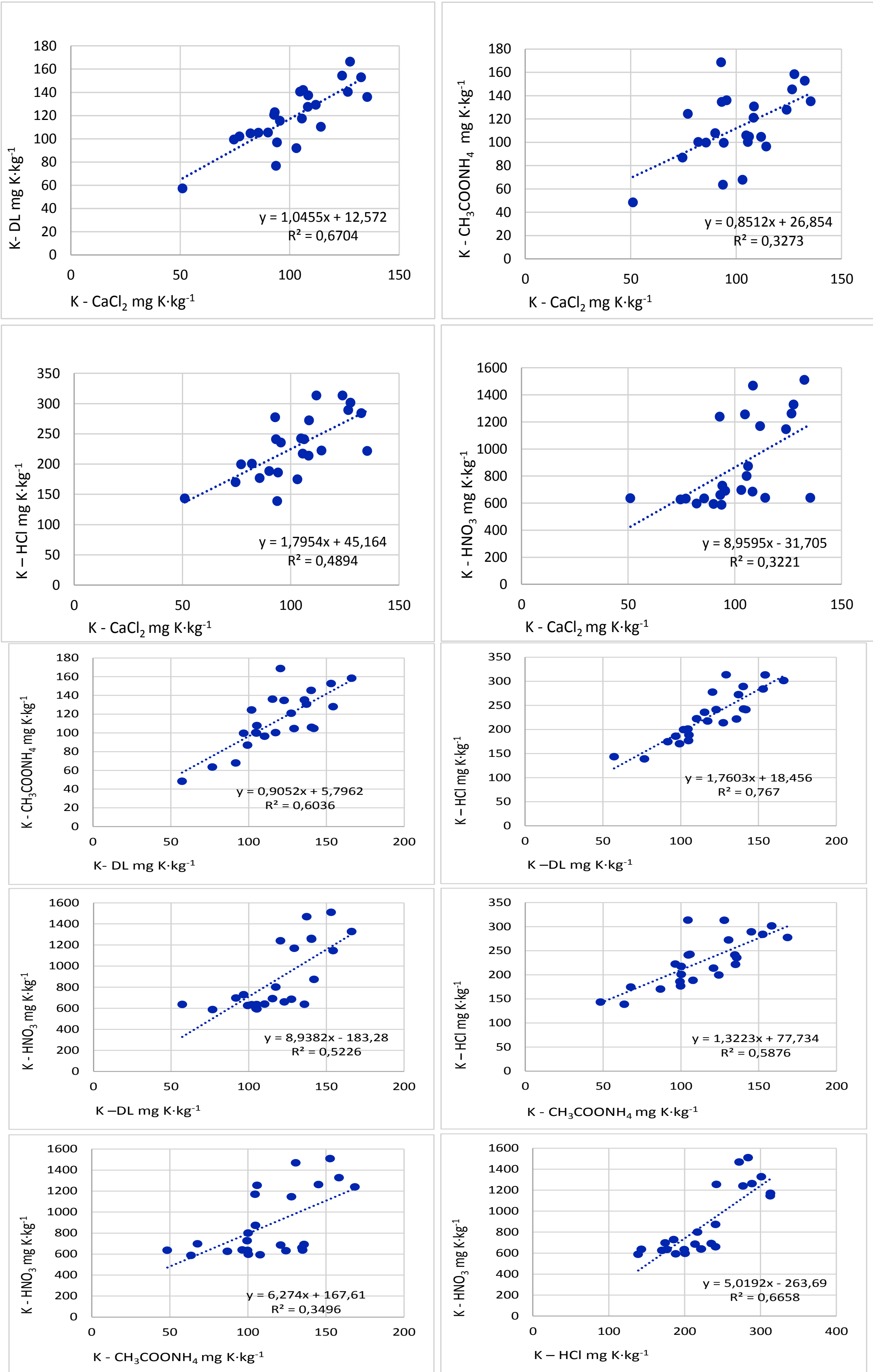
	K - $CaCl_2$	K- [DL]	K - CH_3COONH_4	K – HCl	K - HNO_3
K - $CaCl_2$	1,00	0,82	0,57	0,70	0,57
K- [DL]		1,00	0,78	0,88	0,72
K - CH_3COONH_4			1,00	0,77	0,59
K – HCl				1,00	0,82
K - HNO_3					1,00

Source: own work / Źródło: opracowanie własne



Source: own work / Źródło: opracowanie własne

Fig. 2. Percentage share of analysed forms of potassium in soil samples compared to its content measured by HNO_3 extraction
Rys. 2. Procentowy udział analizowanych form potasu w analizowanych próbkach glebowych w stosunku jego form oznaczonych w HNO_3



Source: own work / Źródło: opracowanie własne

Fig. 3. The relationship between the analyzed potassium forms
Rys. 3. Zależności pomiędzy analizowanymi formami potasu

Figure 3 shows the analysis of regression parameters. The above data suggested a strong predictive power between K-DL and K-$CaCl_2$, K-CH_3COONH_4 and K-DL, K-HCl and K-DL, K-HNO_3 and K-HCl. These relationships allow for the determination of an average content of potassium forms. In contrast, determination coefficient calculated as 0,3221 for K-HNO_3 with K-$CaCl_2$ and 0,3496 for K-HNO_3 with K-CH_3COONH_4 etc. suggested that there is no possibility to predict average contents of potassium forms.

4. Conclusions

The above data suggested:

1. The content of different potassium forms was different in different soil layers and was dependent on fertilisation and irrigation.
2. Irrigation resulted in significant reduction of active, bioavailable and exchangeable K, in particular in upper soil layer.
3. Irrigation and fertilisation with 80 kg N · ha^{-1} led to a significant reduction in the content of active potassium in arable and subsoil layer.
4. Irrigation and fertilisation had the least impact on the content of K-HCl and K-HNO_3.
5. There was a high correlation of R=0,88 between K-DL and K-HCl.

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