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LATENT INFESTATION OF POTATO TUBERS WITH SOFT ROT AND RING ROT PATHOGENS UNDER CHANGING WEATHER CONDITIONS IN UKRAINE

Potato is one of the most important food crops in the world. Cultivation of potatoes is an important segment of the agriculture and economy as a whole in Ukraine. Bacterial diseases such as ring rot caused by Clavibacter sepedonicus, as well as soft rot and blackleg caused by Pectobacterium atrosepticum evoke tremendous losses of the potato crop. Stored seed tubers are the main source of accumulating pathogens in latent form. In addition, potato crop yield and quality are significantly affected by weather conditions. Along with affecting potatoes directly, meteorological factors such as air temperature and humidity can also impact tuber infestation with bacterial pathogens. The ***aim*** *of the study was to monitor the prevalence of bacterial ring rot pathogen C. sepedonicus and soft rot pathogen P. atrosepticum in potato tubers on the territory of Ukraine in 2020 and 2021 years and assess its association with different weather conditions.* ***Methods.*** *Potato seed lots from newly harvested crops in eight regions of Ukraine (Odesa, Kyiv, Donetsk, Kherson, Cherkasy, Mykolaiv, Dnipropetrovsk, and Zhytomyr regions) without visual symptoms of diseases were used for the experiments. The detection of C. sepedonicus and P. atrosepticum was conducted by the immunochemical method DAS ELISA. Basal meteorological data (the sum of precipitation (mm/month) and average air temperature (°C) were obtained from the local meteorological stations. The amplitude of air temperature and the sum of precipitation during potato planting, growing, and harvesting seasons, as well as Sielianinov's hydrothermal coefficient (K) were additionally calculated. The Spearman correlation coefficient was used for the analysis of the correlation between pathogen prevalence and weather parameters.* ***Results****. Both ring rot pathogen C. sepedonicus and soft rot pathogen P. atrosepticum were detected in potato lots from all surveyed regions, but the prevalence of latent infestation varied between 2020 and 2021. In 2020, the highest soft rot pathogen prevalence values were registered for Mykolaiv, Kyiv, and Cherkasy regions (21.7, 10.5, and 10% respectively), where high rainfall levels in May and June were observed. In 2021, potato planting, growing, and harvesting seasons were marked by significantly higher precipitation levels, as compared to 2020, in all regions. Average occurrence values for P.*

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atrosepticum in potato lots were 1.7 times higher than that in 2020. The highest prevalence (40%) was observed in the Donetsk region with extremely high air humidity during the potato growing period. Strong positive correlation (r = 0.721) was found between soft rot pathogen prevalence and K coefficients during the potato growing season, as well as between P. atrosepticum prevalence and the sum of precipitation during planting and early growing seasons. Prevalence of ring rot pathogen didn't differ significantly in 2020 and 2021. The highest C. sepedonicus prevalence was observed in 2020 in the Kyiv region (18.9%), and in 2021 — in the Donetsk region (20%). A moderate positive correlation (r = 0.591) was found between pathogen prevalence and air temperature during planting and early growing season. ***Conclusions.*** *Weather factors such as air temperature and humidity over the planting and early growing potato season can influence progeny tuber infestation with P. atrosepticum and C. sepedonicus. Knowledge of the effect of the changing weather conditions on the susceptibility of potato varieties with different genetic features to infestation with soft rot and ring rot pathogens warrants future investigation since it is crucially important for developing measures for disease control by potato producers.*

Keywords: *potato, Solanum tuberosum, bacterial diseases, Clavibacter sepedonicus, Pectobacterium atrosepticum, weather.*

In terms of growing volumes, potato is the third most significant food crop in the world. Nowadays, potato is grown in more than 150 countries on more than 20 million hectares, and global total potato production surpasses 350 million tons [1, 2]. Ukraine is the fifth largest producer of potatoes in the world, with a production of approximately 20 million tons and grown areas of about 1283.3 thousand hectares [3]. In addition, currently, Ukraine takes second place in the ranking of potato consumption per capita among all countries of the world. Thus, achieving high- quality potato yields is an important issue for Ukraine.

Potatoes are mainly propagated asexually (vegetatively or by cloning) by means of tubers, especially in developing countries, although sexual propagation (by botanical seed, also called true potato seed) is also possible [4]. The predominance of vegetative potato propagation results in accumulating pathogens in planting material in a latent form due to successive tuber-stem-tuber cycles and thus leads to seed potato degeneration and the reduction in yield and/or quality [5—7]. Potato, particularly stored tubers, is affected by about seven bacterial diseases including bacterial soft rot and blackleg, as well as ring rot being serious dangers [8, 9].

In contradistinction to numerous bacterial plant diseases, widespread in natural ecosystems, bacterial soft rot and blackleg are predominantly diseases of agricultural ecosystems. Soft rot is a major potato disease in the world, which causes greater harvest loss than any other bacterial disease, especially in developing countries due to the lack of appropriate storage facilities. *Dickeya* and *Pectobacterium* are the most common and most widely studied bacterial soft rot pathogens [10, 11]. The genus *Dickeya* assembles 12 recognized species and the genus *Pectobacterium* incorporates 19 species. *P. atrosepticum* (formerly *Erwinia carotovora* subsp. *atroseptica*) is a canonical potato soft rot and black leg pathogen and differs from other soft rot pathogens in its relatively narrow host range, being limited to the plant family *Solanaceae* [12, 13]. The prevalence of potato soft rot and black leg on the territory of Ukraine depends on soil and geographical potato growing areas and was the highest in the northern and central parts of Polissia, Carpathian foothills, and Bukovyna as of 2019 [14]. Losses of potato crops caused by soft rot and blackleg depend on weather conditions and the pathogen aggressiveness and can range from 1—2 to 50—75%.

Potato ring rot, caused by *C. sepedonicus,* is widespread throughout Ukraine [15]. Crop losses due to this disease during both the potato vegetation period and storage can reach 45%. In some cases, potato ring rot can be the main cause of seed/planting material culling. Potato yield losses from this disease have increased significantly in recent years in Ukraine due to tuber mechanical damages over the cultivation, harvesting, and storage, which facilitates infestation [16]. Currently, *C. sepedonicus* is under a

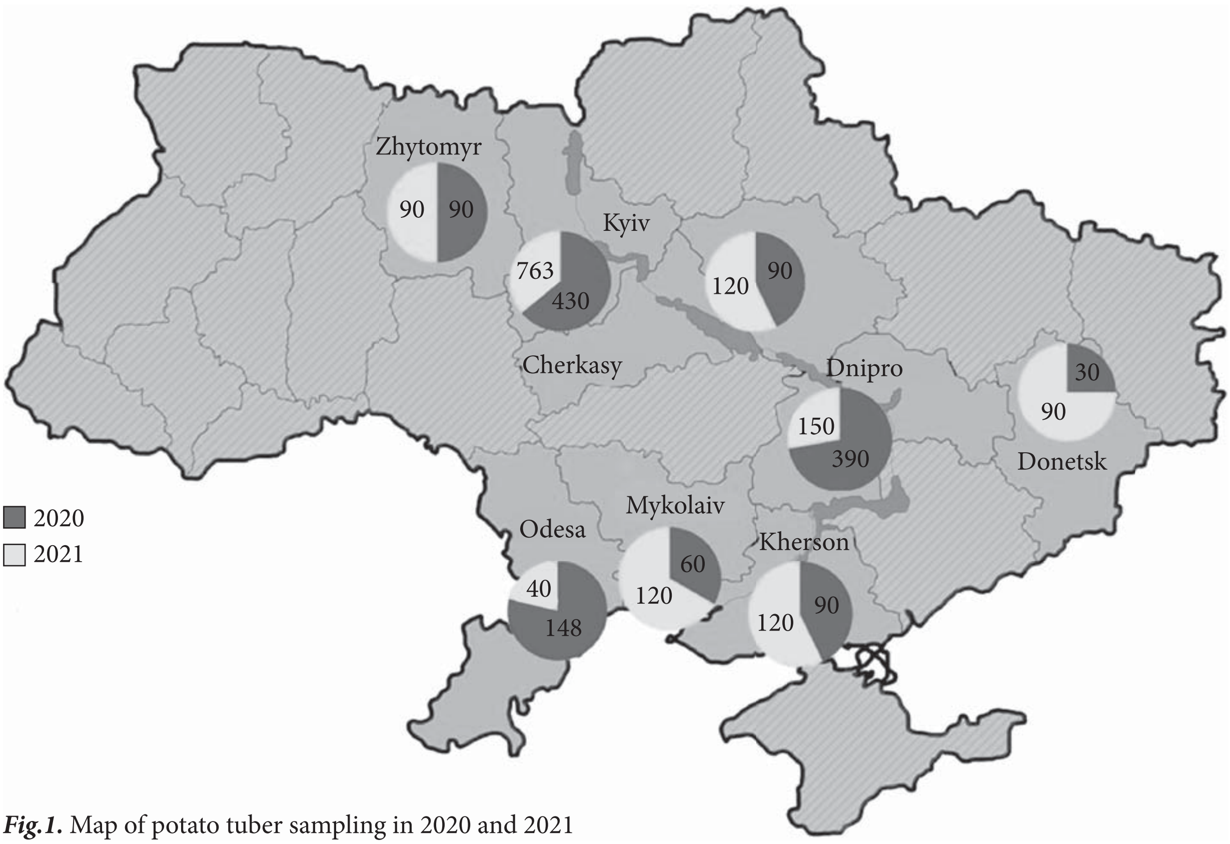

Fig.1. Map of potato tuber sampling in 2020 and 2021

special control scheme in many countries of the world and is classified as a regulated non-quarantine pathogen in Ukraine [17, 18]. Potato ring rot is difficult to control, and primary infections are soon followed by secondary ones caused by *Pectobacterium* soft rotting bacteria [19].

Bacterioses are among the most important biotic limitation factors of potato production in all climatic regions of the world [20]. All the factors influencing bacteriosis development should be clarified, and appropriate management strategies should be adhered to mitigate potato yield losses. Global environmental changes are among these factors. The concept of the «disease triangle» in plant pathology indicates the importance of the interaction of pathogens and plants with the environment. For the development of a disease, a susceptible host plant, a virulent pathogen, and proper environmental conditions are required, as the absence of favorable conditions for any of these factors does not lead to the development of the disease. Plants and their pathogens both require optimal environmental conditions for their growth and development. The three-way environment-host-pathogen interaction ranges from interactions that fully favor disease (disease optima) to those that support healthy plants [21, 22].

This study was **aimed** at monitoring the prevalence of bacterial ring rot pathogen *C. sepedonicus* and soft rot and blackleg pathogen *P. atrosepticum* in potato tubers on the territory of Ukraine in 2020 and 2021 and assessing its association with different weather conditions.

Materials and methods. The experiments were conducted at the diagnostic center of LLC «Syngenta». For each year (2020 and 2021), potato seed sets from newly harvested crops without visual symptoms of diseases were used for the experiments. In 2020, 1661 potato tubers from 8 regions of Ukraine, including the Odesa (148 tubers), Kyiv (763), Donetsk (30), Kherson (90), Cherkasy (90), Mykolaiv (60), Dnipropetrovsk (390), and Zhytomyr (90) regions were examined. In 2021, 1160 potato tubers from the same 8 regions of Ukraine were investigated: Odesa (40 tubers), Kyiv (430), Donetsk (90), Kherson (120), Cherkasy (120), Mykolaiv (120), Dnipropetrovsk (150), and Zhytomyr (90) regions (Fig. 1).

Potato tuber sampling and average sample preparation were performed by authorized persons in each farm according to DSTU 4014:2001 [24]. Characteristics of potato varieties provided by authorized persons are summarized in Table 1.

The detection of bacterial pathogens *C. sepedonicus* and *P. atrosepticum* was performed by the immunochemical method DAS ELISA using the commercial test systems LOEWE® Standard Complete Kit (Germany) according to the manufacturer's recommendations, as described previously [25]. Tubers samples were placed in bags for homogenization «Extraction bags Universal 12 x 15 cm» (BIOREBA AG, Switzerland) with sample buffer and homogenized using a semi-automatic homogenizer HOMEX 6 (Bioreba AG, Switzerland) with passive deposition of plant tissues. For plate incubating and washing, a thermostat for microplates PST- 60HL-4 (Biosan, Latvia) and a PW-40 washer (Bio-Rad, USA) were used respectively. The enzymatic reaction was evaluated photometrically at a wavelength of 405 nm using a SUNRISE microplate photometer (TECAN Austria GmbH, Austria). The Magellan V.7.1 program was used to process the results. The bacteria infestation prevalence was calculated using the formula: Prevalence = (n*100)/N, where n is the number of affected tubers in the sample, pcs.; N is the total number of tubers in the sample, pcs.

For each region, meteorological data (the sum of precipitation, mm/month, and average air temperature, °C) obtained from the local meteorological station were collected. The temperature amplitude was calculated as the difference between the maximum and minimum average air temperature that occurred within a potato growing time period (from April to September). The precipitation amplitude was calculated as the difference between the maximum and minimum sum of precipitation that occurred within a potato growing period (from April to September). The sum of precipitation was calculated by summing the monthly sums of precipitation during a potato growing period (from April to September). Additionally, Sielianinov's hydrothermal coefficient was calculated to determine temporal fluctuations of meteorological conditions and their impact on pathogen prevalence. The hydrothermal coefficient (K) was calculated on the basis of monthly sums of precipitation (P) and the monthly sum of mean daily temperatures (Σt), using the following formula: $K = P/0.1\ \Sigma t$. The values of Sielianinov's coefficient were classified as follows: <0.40 — extremely dry (ed), 0.41—0.70 — very dry (vd), 0.71—1.0 — dry (d),

Table 1. **Characteristics of potato varieties**

Region	Variety	Maturity group	Blackleg resistance
	2020		
Odesa	Miranda, SOLANA GmbH (Germany)	Early	Low, Medium
	Laperla, SOLANA GmbH (Germany)	Very early	N/I*
	Riviera, Mts. Boerhave (Netherlands)	Very early	Medium to high
Mykolaiv	Riviera, Mts. Boerhave (Netherlands)	Very early	Medium to high
Kherson	Riviera, Mts. Boerhave (Netherlands)	Very early	Medium to high
	Arizona, AGRICO RESEARCH BV (Netherlands)	Second early	Medium
Dnipropetrovsk	N/P**		

Continuation of Table 1

Region	Variety	Maturity group	Blackleg resistance
Donetsk	Monte Carlo, TPC (Netherlands)	Middle early	N/I
Cherkasy	N/P**		
Kyiv	Bellarosa, EUROPLANT Pflanzenzucht GmbH (Germany)	Very early to early	N/I
	Colomba, HZPC (Netherlands)	Early	N/I
	Mozart, HZPC (Netherlands)	Medium late	N/I
	Granada, SOLANA GmbH (Germany)	Medium early	High
	Toscana, SOLANA GmbH (Germany)	Medium early	High
	Queen Anne, SOLANA GmbH (Germany)	Early	High
	Labella, SOLANA GmbH (Germany)	Medium early	Medium, High
	Lilly, SOLANA GmbH (Germany)	Medium early	High
	Soraya, Greenvale Seed (UK)	Early	High
	Sunshine, SOLANA GmbH (Germany)	Very early to early	High
	Opal, SOLANA GmbH (Germany)	Medium early	High
	Red Lady, SOLANA GmbH (Germany)	Medium early	Medium to high
	Prada, SOLANA GmbH (Germany)	Very early	Medium
	Arizona, AGRICO RESEARCH BV (Netherlands)	Second early	Medium
	Rudolph, AGRICO UK (UK)	Early	Low
	Arsenal, AGRICO UK (UK)	Maincrop	N/I
	Riviera, Mts. Boerhave (Netherlands)	Very early	Medium to high
Zhytomyr	Colomba, HZPC (Netherlands)	Early	N/I
	Riviera, Mts. Boerhave (Netherlands)	Very early	Medium, high
	Soraya, Greenvale Seed (UK)	Early	High
	2021		
Odessa	N/P**		
Mykolaiv	Natalia, SOLANA GmbH (Germany)	Early	High
	Prada, SOLANA GmbH (Germany)	Very early	Medium
	Rodriga, SOLANA GmbH (Germany)	Early	High
	Sunshine, SOLANA GmbH (Germany)	Very early to early	High
Kherson	Bellarosa, EUROPLANT Pflanzenzucht GmbH (Germany)	Very early to early	N/I
	Vineta, EUROPLANT Pflanzenzucht GmbH (Germany)	Early	N/I
	Arizona, AGRICO RESEARCH BV (Netherlands)	Second early	Medium
Dnipropetrovsk	N/P**		
Donetsk	Arizona, AGRICO RESEARCH BV (Netherlands)	Second early	Medium
	Picasso, GEBR. HOLSTEIN (Netherlands)	Maincrop	Low
	Monte Carlo, TPC (Netherlands)	Middle early	N/I
Cherkasy	Labella, SOLANA GmbH (Germany)	Medium early	Medium, High
	Belmonda, SOLANA GmbH (Germany)	Medium early	Medium, High
Kyiv	Picasso, GEBR. HOLSTEIN (Netherlands)	Maincrop	Low
	Arizona, AGRICO RESEARCH BV (Netherlands)	Second early	Medium
Zhytomyr	N/P**		

*No information about sensitivity/resistance to blackleg in variety characteristics provided by producers; **data concerning potato varieties were not provided by authorized persons.

1.01—1.3 — quite dry (qd), 1.31—1.6 — optimum (o), 1.61—2.0 — moderately wet (mw), 2.01—2.50 — wet (w), 2.51—3 — very wet (vw), >3 — extremely wet (ew) [26].

Data on the sum of precipitations during potato growing time are presented as mean ± SD. These data were tested using the Kolmogorov—Smirnov test for a normal distribution before other statistical tests. Statistical differences were calculated using a two-tailed t-test. Differences were considered significant at $p < 0.05$. For each meteorological variable measured (monthly sum of precipitation, monthly sum of mean daily temperatures, and Sielianinov's coefficient), a separate correlation analysis with potato soft rot and ring rot pathogen prevalence in tubers from newly harvested crops in different regions was conducted. The Spearman correlation coefficient was used [27]. The statistical significance of the found Spearman correlation coefficient values was checked via calculating by the t-statistic formula:

$$t = \frac{r\sqrt{(N-2)}}{\sqrt{(1-r^2)}}$$

where t — Student's distribution, r — Spearman correlation, N — sample size, 2 — degrees of freedom [28].

Results. During the period 2020—2021, weather conditions differed in all regions of the Ukraine. The potato planting season in Ukraine in 2020 turned out to be dry for most regions (Table 2). Low temperatures were noted in the central, eastern, and northern regions, and temperatures in the southern regions were optimal for potato planting. May turned out to be gen-

Table 2. **Weather conditions during the period of planting, vegetation, and harvesting of potatoes in 2020 [19]**

2020		Odesa	Mykolaiv	Kherson	Dnipro-petrovsk	Donetsk	Cherkasy	Kyiv	Zhytomyr
April (IV)	ΣR*, мм	8.0	8.0	10.7	12.2	13.7	22.9	27.1	21.2
	t_{avg}**, °C	11.2	10.3	10.1	9.3	8.7	9.3	9.1	9.1
K***		0.71(d)	0.78 (d)	1.06 (qd)	—	—	—	—	—
May (V)	ΣR*, мм	58.7	51.9	36.6	63.1	45.7	111.2	124.5	116.7
	t_{avg}**, °C	14.8	14.4	15.1	14.7	14.6	13.2	12.4	11.9
K		4.0 (ew)	3.60 (ew)	2.42 (vw)	4.29 (ew)	3.13 (ew)	8.42 (ew)	10.04 (ew)	9.81(ew)
June (VI)	ΣR*, мм	41.8	42.5	30.5	35	29.8	69.5	65.7	78.5
	t_{avg}**, °C	22.1	22.5	22.9	22.6	22.4	21.3	20.9	20.1
K		1.89 (mw)	1.89 (mw)	1.33 (o)	1.56 (o)	1.33 (o)	3.26 (ew)	3.14 (ew)	3.91 (ew)
July (VII)	ΣR*, мм	22.4	21.5	14.5	7.3	27.6	23.9	35.6	43.2
	t_{avg}**, °C	24.8	24.9	25.9	24.6	24.7	22.4	21.4	20.3
K		0.9 (d)	0.86 (d)	0.56 (ed)	0.30 (ed)	1.12 (qd)	1.07 (d)	1.66 (mw)	2.13 (w)
August (VIII)	ΣR*, мм	3.4	4.2	7	5.9	6.1	7.2	13.9	25.2
	v	23.9	23.9	24.6	23.4	23	22.3	21.2	20.5
K		0.14 (ed)	0.18 (ed)	0.28 (ed)	0.25 (ed)	0.27 (ed)	0.32 (ed)	0.66 (vd)	1.23 (qd)
September (IX)	ΣR*, мм	9.9	18.4	35.9	22.6	0.8	31	24.6	29.5
	t_{avg}**, °C	20.6	20.7	21.2	20.2	19.8	19.2	18.4	17.5
K		0.48 (vd)	0.89 (d)	1.69 (mw)	1.12 (qd)	0.04 (ed)	1.61 (mw)	1.34 (o)	1.69 (mw)

*ΣR is the sum of precipitation, mm; ** t_{avg} is the average air temperature, °C; *** K is Sielianinov's hydrothermal coefficient.

erous with abundant rainfalls, and the largest amount of precipitation was recorded in the northern regions, as well as in the Cherkasy region. The Sielianinov hydrothermal coefficient (K), which was calculated only for the regions where the average air temperature excessed 10 °C, showed thatin 2020, April was quite dry, whereas in May, K values ranged from 2.42 for Kherson to 10.04 for Kyiv, indicating sufficient and sometimes excessive moisture.

The growing season of 2020 was characterized by sufficient and excessive moisture in all regions in June. However, in July, the K coefficient indicated drought of varying intensity in most regions, except for Kyiv and Zhytomyr regions, where sufficient moisture was observed. The potato harvesting period in 2020 was marked by quite drought weather with high temperatures in all regions in August, while in September, dry weather persisted in Odesa, Mykolaiv, Donetsk, and Dnipropetrovsk regions.

The planting season in 2021 was characterized by slightly lower air temperatures and significantly higher rainfall levels, as compared to 2020, in all regions (Table 3). K coefficient values in May were rather similar to those in 2020. The growing season in 2021 was marked by significantly increased precipitation levels in comparison with 2020 in virtually all regions with some exceptions (Kyiv region in June, Zhytomyr region in June and July).The harvesting season in 2021 was characterized by lower air temperatures, as compared to 2020, in all regions. Rainfall levels varied significantly from very low in the Odesa region to quite high in the Zhytomyr region.

Table 3. **Weather conditions during the period of planting, vegetation, and harvesting of potatoes in 2021 [19]**

2021		Odesa	Mykolaiv	Kherson	Dnipro-petrovsk	Donetsk	Cherkasy	Kyiv	Zhytomyr
April (IV)	ΣR*, мм	43.5	45.8	42	45.2	31.6	52.5	40.1	44.2
	t_{avg} **, °C	9.5	9.3	9.9	9.6	9.6	8.4	8.1	7.6
K		—	—	—	—	—	—	—	—
May (V)	ΣR*, мм	60.5	51.9	25.8	29.8	41.6	59.4	104.5	117.0
	t_{avg} **, °C	16.2	16.2	17.1	16.7	17.1	15.1	14.3	13.6
K		3.73 (ew)	3.20 (ew)	1.51(o)	1.78 (mw)	2.43 (w)	3.93 (ew)	7.31 (ew)	8.60 (ew)
June (VI)	ΣR*, мм	114	90.2	75. 0	129.3	130.9	77.8	50.7	47.6
	t_{avg} **, °C	21.2	21.5	21.8	21.2	21.2	20.4	20.4	20.1
K		5.38 (ew)	4.20 (ew)	3.44 (ew)	6.10 (ew)	6.18 (ew)	3.81 (ew)	2.49 (w)	2.36 (w)
July (VII)	ΣR*, мм	37.9	36.5	59. 9	44.9	44.8	36.8	50	44.2
	t t_{avg} **, °C	26	26.5	27.1	26.3	26.2	25.2	24.7	24
K		1.46 (o)	1.38 (o)	2.21 (w)	1.71 (mw)	1.71 (mw)	1.46 (o)	2.02 (w)	1.84 (mw)
August (VIII)	ΣR*, мм	13.9	12	21.7	17.1	11.7	46.9	37.5	60.5
	t_{avg} **, °C	24.7	25.3	26.5	26	26.3	23.4	22	20.8
K		0.56 (vd)	0.47 (vd)	0.82 (d)	0.66 (vd)	0.45 (vd)	2.00 (mw)	1.71 (mw)	2.91 (vw)
September (IX)	ΣR*, мм	10.9	22.5	12.2	16.9	26.9	25.2	27. 6	28.4
	t_{avg} **, °C	16.9	16.3	17	15.6	15.8	14.6	13.9	13.6
K		0.65 (vd)	1.38 (o)	0.72 (d)	1.08 (qd)	1.70 (mw)	1.73 (mw)	1.99 (mw)	2.09 (w)

*ΣR is the sum of precipitation, mm; ** t_{avg} is the average air temperature, ˚C; *** K — Sielianinov's hydrothermal coefficient.

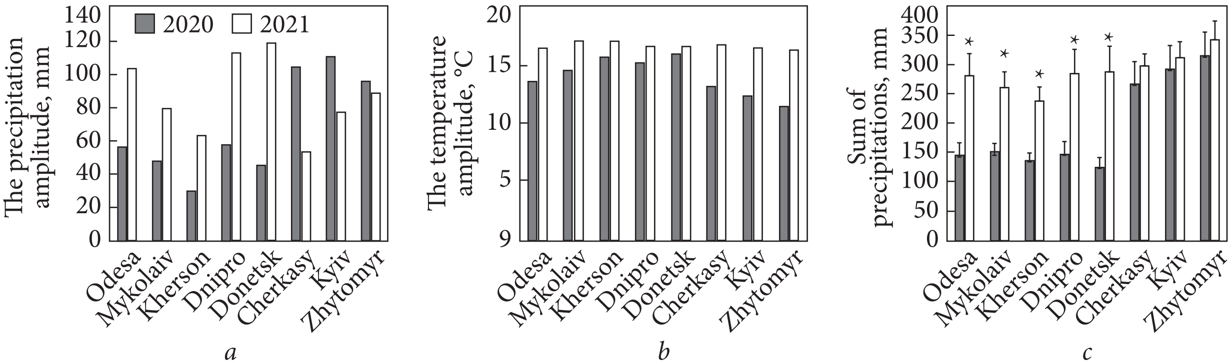

Fig. 2. Amplitude of the sum of precipitation (*a*), amplitude of average air temperature (*b*), and sum of the precipitation during the planting, growing, and harvesting season (*c*) in 2020 and 2021 in surveyed regions of Ukraine. Data on diagram *c* are presented as mean ± SD. *$p < 0.05$ as compared to 2020

In addition to basal weather characteristics (monthly average temperature and sum of rainfall), we also calculated their amplitudes during the potato growing time (from April to September) and the sum of precipitations (Fig. 2). Precipitation variations were significantly higher in 2021 as compared to 2020 in most regions except Kyiv, Cherkasy, and Zhytomyr ones (Fig. 2, *a*). The Maximum precipitation amplitude in 2021 was registered in the Donetsk region: 2.7 times higher than that in 2020. Virtually, no differences were observed in precipitation amplitude in 2020 and 2021 in the Zhytomyr region. A minor increase in temperature amplitude in 2021 was observed in all regions, most pronounced in Kyiv and Zhytomyr regions (Fig. 2, *b*). The sum of precipitations during potato growing time was significantly higher in 2021 in comparison with 2020 in most regions except the Cherkasy, Kyiv, and Zhytomyr regions (Fig. 2, *c*).

Both ring rot pathogen *C. sepedonicus* and soft rot and blackleg pathogen *P. atrosepticum* were detected in all surveyed regions, but the prevalence of latent infestation varied between 2020 and 2021 in virtually all locations (Fig. 3). In 2020, *C. sepedonicus* was detected in tuber samples from all regions except Kherson and Zhytomyr (Fig. 3, *a*). In 2020, the Kherson region was distinguished from the other regions by the lowest K values over the time of potato growing due to the low precipitation level. The Zhytomyr region was characterized by the lowest monthly temperatures in comparison with the other regions during the potato growing period (Table 2). The highest prevalence of *C. sepedonicus* this year was observed in the Kyiv and Dnipropetrovsk regions: 18.9% and 12.6% respectively. In the Kyiv region, the highest rainfall levels during potato planting and growth initiating were observed. Next year, the situation with latent infection of potato tubers with ring rot pathogen has changed. Lesioned tubers were detected in samples from Kherson (3.3%) and Zhytomyr (2.2%) regions. In addition, *C. sepedonicus* occurrence values were increased in Odesa, Donetsk, and Cherkasy regions. The highest proportion of lesioned tubers was detected in the samples from the Donetsk region — 20%, which is sixfold higher than in 2020. This region was characterized by the most significant variations of rainfall over the period of potato growing in 2021. At the same time, the pathogen prevalence in the Kyiv (lowest amplitude of precipitation level), Dnipropetrovsk (lowest precipitation level during potato planting and growth initiating period),

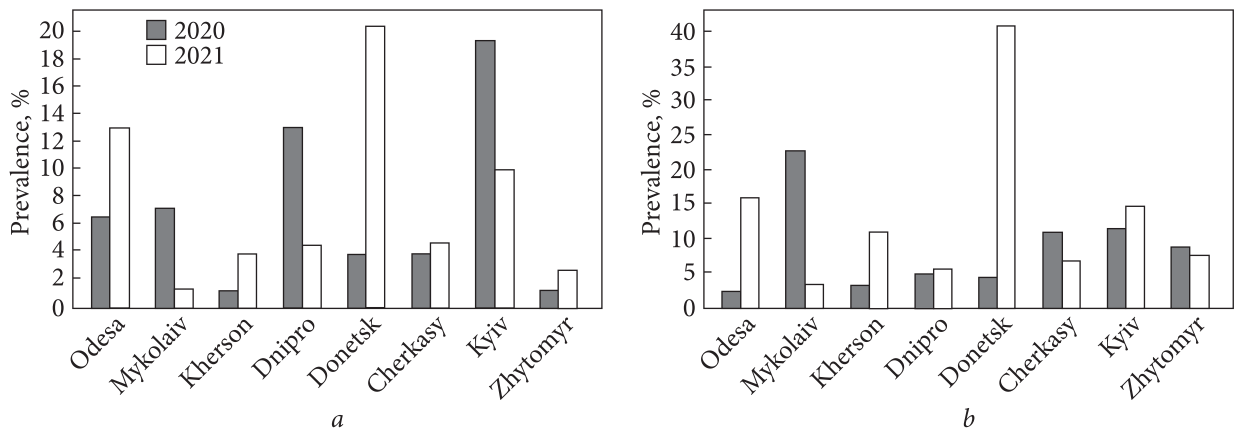

Fig. 3. Prevalence of *C. sepedonicus* (*a*) and *P. atrosepticum* (*b*) in potato lots from newly harvested crops in different regions of Ukraine in 2020—2021

as well as in Mykolaiv (lowest sum of precipitation over the time of potato growing) regions — on the contrary, decreased by 2, 3, and 8 times respectively.

P. atrosepticum was also detected in most surveyed regions in 2020 except Odesa region (Fig. 3, *b*). The average value of soft rot and blackleg pathogen prevalence in the new harvest tubers on the territory of Ukraine was close to that for *C. sepedonicus*: 7.4% vs 6.4% respectively. That year, the highest prevalence values were registered for the Mykolaiv, Kyiv, and Cherkasy regions: 21.7%, 10.5%, and 10% respectively. It is necessary to note that potato varieties grown in the Mykolaiv region were characterized by breeders as those with medium resistance to blackleg and most varieties in the Kyiv region — as those with high and medium to high resistance (see Table 1). In 2021, the average occurrence of the blackleg pathogen throughout the country increased by 1.7 times as compared to 2020: 12.3% vs 7.4% respectively, which was accompanied by a 1.5-fold increase in the average sum of precipitation over the time of potato growing throughout all regions. *P. atrosepticum* was detected in the tubers of potato samples from the Odesa region (15%), and prevalence values for the pathogen were increased in most regions except the Mykolaiv and Cherkasy regions, where prevalence values decreased by 8.7 and 1.7 times respectively, and Zhytomyr region, where the situation didn't change significantly. The highest soft rot and blackleg pathogen occurrence values were registered in the Donetsk region — 40%, which is 12.1 times higher than in 2020. It is necessary to note, that resistance of potato varieties grown in regions with increased pathogen prevalence varied significantly from low to high (according to breeders' data).

The Spearman correlation analysis revealed associations between the *P. atrosepticum* prevalence and K coefficient values in the potato growing season (June-July) ($r = 0.721$, $p < 0.05$) (Fig. 4, *a*). A strong positive correlation was also found between *P. atrosepticum* prevalence and monthly sums of precipitation during the potato growing season ($r = 0.721$, $p < 0.05$) (Fig. 4, *b*). In addition, a strong negative correlation was detected between *P. atrosepticum* prevalence and the monthly sum of mean daily temperatures during the potato harvesting season (August-September) ($r = -0.736$, $p < 0.05$) (Fig. 4, *c*). As for *C. sepedonicus*, we revealed only moderate correlation between the prevalence of the pathogen and the monthly sum of mean daily temperatures during the potato planting season (May) ($r = 0.591$, $p \geq 0.05$) (Fig. 4, *d*).

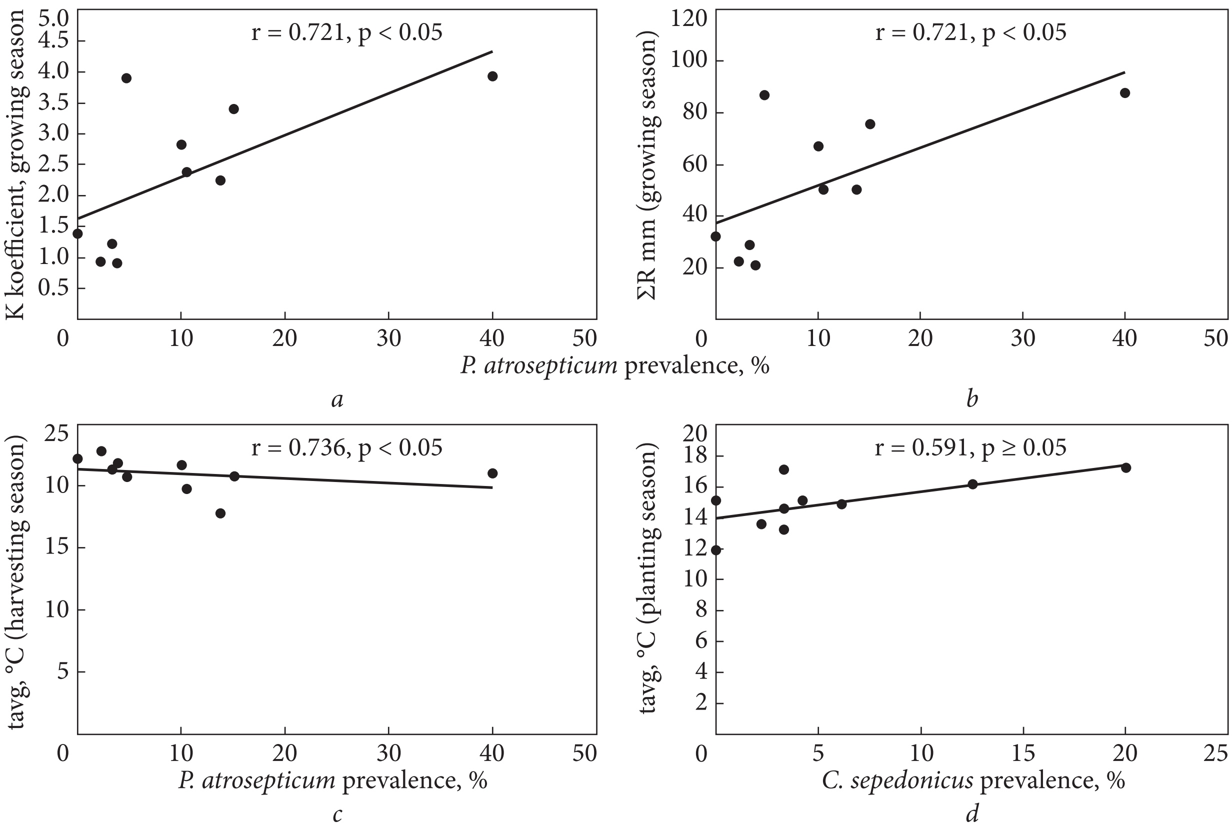

Fig. 4. Correlation between the prevalence of *P. atrosepticum* and *C. sepedonicus* and weather parameters

Discussion. The agro-industrial complex is an important sector of the economy of Ukraine, which forms food, economic, ecological, and energy security and ensures the development of technologically related branches. The cultivation of potatoes is one of the most important branches of agricultural production in Ukraine [22]. The quality and quantity of the potato crop are significantly influenced by climatic conditions during planting, growing, and harvesting season, since abiotic and biotic stresses acting in tandem (disease develops only under permissive environmental conditions) cause huge crop losses [29]. One of the biggest threats to potato productivity is the loss caused by bacterial diseases, which, once introduced into the crop, can persist and spread in the agricultural environment through latent (asymptomatic) infections [30]. The major source of field inoculum for bacteria is the latently infected seed (mother) tubers [31]. Nowadays, potato soft rot and blackleg caused by pectolytic bacteria along with potato ring rot caused by *C. sepedonicus* receive increased attention. Potato growing industry harm wreaked by ring rot, soft rot, and blackleg necessitates deep insight into the biology of the causal agents including the impact of environmental factors on the degree of plant infestation, which is very important for the epidemiology of the diseases [8]. Tuber infestation by rot pathogens depends on various genetic features, as well as on many environmental factors including air and soil temperature, air and soil humidity, etc. Weather changes, which are highly unpredictable in their characteristics, can impact the plant disease triangle in different ways. Literature data concerning the impact of weather conditions, particularly air temperature and precipitation level, on the latent infestation of potato tubers with soft rot and blackleg and ring rot are quite scarce and controversial.

P. atrosepticum, a temperature-sensitive species, mainly occurs in temperate climates and is able to grow only up to 33 °C and causes disease primarily at 18—22 °C. Temperature plays a decisive role in mother-tuber rotting, while *P. atrosepticum* is more pathogenic at lower temperatures (< 25 °C) [31]. In addition, temperature fluctuations can stipulate the expression of pathogenicity factors and in such a way impact species selection [32, 33]. Kaczynska et al. reported about examined pool of 29 thermoregulated genes of *P. atrosepticum* (including those associated with pathogenicity), 14 of which were up-regulated at 18 °C, while 15 others — at 28 °C. Authors supposed involvement of these genes in the pathogen ecological adaptation [34]. According to Pe´rombelon et al. [35], another equally important environmental factor for mother-tuber rotting is soil humidity since water film on the tuber surface creates anaerobic conditions in tuber tissues, which facilitates bacterial multiplications. On the basis of laboratory experiments, Moh et al. [36] opine that temperature is the most influential environmental factor for tuber infestation followed by bacteria load and humidity. Our own results indicate that both air temperature and precipitation level play equally important roles in progeny tuber infestation with *P. atrosepticum*. Regions with sharply elevated prevalence of soft rot and blackleg pathogens in 2021 were characterized by the highest air temperature values during the early growing season, 17.2 °C, which is the closest to the optimum for activating thermoregulated genes associated with pathogenicity. The Donetsk region with the highest prevalence value was also marked by the highest rainfall level during the early growing season and the highest sum of precipitation increase as compared to 2020. In addition, we have revealed a strong positive correlation between *P. atrosepticum* prevalence and K coefficient during the growing season. According to Aung et al. [37], high atmospheric humidity suppresses the R gene-mediated plant hypersensitive response. It can be one of the mechanisms of decreasing resistance to the infestation with soft rot pathogen [38]. The impact of genetic features of potato varieties cannot be ruled out as well since in the Kherson region, where a spike in *P. atrosepticum* prevalence was observed in 2021, potato varieties have overall lower resilience to blackleg used. At the same time, in the Donetsk region, the same variety was grown in 2020 and 2021, which nevertheless didn't affect the infestation spike in 2021. Our findings are consistent with the data of Liaquat et al. [39], who revealed a significant correlation between several weather parameters and the development of soft rot and blackleg in different potato varieties irrespective of their genetic characteristics.

C. sepedonicus has a low optimum growth temperature (20—23 °C) and is limited mainly to cooler potato-growing regions. High temperatures stimulate the development of the disease, and lower temperatures favor the survival of the pathogen. Inoculum concentration, variety, geographic location, and the interaction of these factors affect the manifestation of symptoms in the field. Symptom expression in greenhouse experiments occurred more often at 22—35 °C than at 16—18 °C or 4 °C. In addition, the relatively high temperature of the soil promotes the development of the disease [19]. Meteorological factors such as relative humidity, temperature, and soil profile also have a significant impact on the development of ring rot in potato plants. According to Pietraszko et al., the infestation rate with ring rot pathogen decreases with increasing air temperature (over the optimum) and the rainfall level, and high soil humidity can also interfere with infection [40]. Gryn et al. [26] state that air and soil temperatures during the initial potato growing season do not substantially influence the number of potato plant tubers infested by ring rot pathogen. Our own observations somewhat contradict this statement since we revealed a moderate positive correlation between *C. sepedonicus* prevalence and air temperature during the initial potato growing period. Our findings are in agreement with the data concerning the correlation between air temperature during the initial plant growth and the expression of virulence genes of *Clavibacter* species affecting tomatoes [41]. The extremely increased precipitation level in 2021 did not change substantially the average prevalence of ring rot pathogen in surveyed regions as compared to that in 2020. This may indicate more importance of air temperature than rainfall level for infestation. The sensitivity to ring rot is not recorded in certificates of potato varieties grown on the territory of Ukraine and requires future investigation.

Thus, the prevalence of soft rot and blackleg pathogen *P. atrosepticum* in potato tubers is strongly correlated with the precipitation level. It can be associated with the negative effect of high atmospheric humidity on the function and activity of R genes mediating an early localized cell death at the site of pathogen ingress and, as a result, disease resistance. The high prevalence of *P. atrosepticum* in selected regions is associated with air temperature during planting and early growing seasons, which is close to optimal for the activation of some thermoregulated genes associated with bacteria pathogenicity. The prevalence of ring rot pathogen *C. sepedonicus* in potato tubers moderately correlates with air temperature during planting and early growing periods. The most likely reason would be the activation of the expression of virulence genes, which is inherent to phytopathogenic representatives of the genus *Clavibacter* during the late spring period. Taken together, our findings indicate that weather factors such as air temperature and humidity during planting and early growing potato seasons can impact progeny tuber infestation with soft rot and ring rot pathogens. Understanding the reaction of potato cultivars with different genetically determined susceptibilities to soft rot and ring rot with changing weather conditions is crucially important for potato producers in order to develop measures for these diseases' control and warrants future investigation.

Study limitations. The study has certain limitations, including a lack of information about potato varieties, which, unfortunately, was not provided by farmers. In addition, the study did not include potato samples from the western regions of Ukraine.

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ЛАТЕНТНЕ УРАЖЕННЯ БУЛЬБ КАРТОПЛІ ЗБУДНИКАМИ М'ЯКОЇ ТА КІЛЬЦЕВОЇ ГНИЛЕЙ ЗА МІНЛИВИХ ПОГОДНИХ УМОВ В УКРАЇНІ

Картопля є однією з найважливіших продовольчих культур у світі. Картоплярство є важливою галуззю сільського господарства та економіки України в цілому. Бактеріальні хвороби, такі як кільцева гниль, викликана *Clavibacter sepedonicus*, а також м'яка гниль і чорна ніжка, викликані *Pectobacterium atrosepticum* спричинюють великі втрати врожаю картоплі. Насіннєві бульби, що довго зберігаються**,** є основним джерелом накопичення патогенів у латентній формі. Крім того, на врожайність та якість картоплі істотно впливають погодні умови. Окрім безпосереднього впливу на картоплю, метеорологічні фактори, такі як температура повітря та вологість, також можуть впливати на зараження бульб патогенами. **Метою** роботи був моніторинг поширеності збудника бактеріальної кільцевої гнилі *C. sepedonicus* та збудника м'якої гнилі і чорної ніжки *P. atrosepticum* у бульбах картоплі на території України в 2020—2021 роках та оцінка її зв'язку з різними погодними умовами. **Методи**. Для дослідів використовували партії садівної картоплі свіжозібраного врожаю з восьми областей України (Одеської, Київської, Донецької, Херсонської, Черкаської, Миколаївської, Дніпропетровської, Житомирської) без візуальних симптомів захворювань. Виявлення *C. sepedonicus* та *P. atrosepticum* проводили імунохімічним методом DAS ELISA. Базові метеорологічні показники (сума опадів, мм/міс., та середня температура повітря, °C) отримані з місцевих метеостанцій. Додатково розраховували амплітуду температури повітря та суми опадів під час посадки, вегетації та збору врожаю картоплі, а також гідротермічний коефіцієнт Селянінова (К). Для аналізу взаємозв'язку між поширеністю збудника та погодними параметрами використовували коефіцієнт кореляції Спірмена. **Результати.** *C. sepedonicus* та *P. atrocepticum* виявлено в партіях картоплі з усіх обстежених регіонів, але поширеність латентної інвазії коливалася між 2020 та 2021 роками. У 2020 році найвищі показники поширеності збудника м'якої гнилі були зареєстровані для Миколаївської, Київської та Черкаської областей (відповідно 21.7 %, 10.5% та 10 %) з високою кількістю опадів у травні та червні. У 2021 році сезон посадки, вегетації та збору врожаю картоплі відзначився значно більшою кількістю опадів порівняно з 2020 роком у всіх регіонах. Середні показники виявлення *P. atrosepticum* у партіях картоплі в досліджуваних регіонах були в 1.7 рази вищими, ніж у 2020 р. Найвищу поширеність спостерігали в Донецькій області (40 %) з надзвичайно високою вологістю повітря в період вегетації картоплі. Виявлено сильний позитивний кореляційний зв'язок (r = 0.721) між поширеністю збудника м'якої гнилі та значеннями коефіцієнта К протягом вегетаційного періоду картоплі, а також між поширеністю *P. atrosepticum* та сумою опадів у період посадки та на початку вегетації. Поширеність збудника кільцевої гнилі суттєво не відрізнялася у 2020 та 2021 роках. Найвищий ступінь поширення *C. sepedonicus* спостерігали у 2020 році в Київській області (18.9%), а у 2021 році — у Донецькій області (20 %). Виявлено помірну позитивну кореляцію (r = 0.591) між поширеністю збудника та температурою повітря під час посадки та на початку вегетації картоплі. **Висновки.** Погодні фактори, такі як температура повітря та вологість у період посадки та початку вегетації картоплі можуть впливати на зараження дочірніх бульб *P. atrosepticum* та *C. sepedonicus*. Знання про вплив зміни погодних умов на сприйнятливість сортів картоплі з різними генетичними особливостями до зараження збудниками м'якої та кільцевої гнилей вимагає подальших досліджень, оскільки це надзвичайно важливо для розробки заходів контролю збудників хвороб картоплі.

Ключові слова: *картопля, Solanum tuberosum, бактеріальні хвороби, Clavibacter sepedonicus, Pectobacterium atrosepticum, погода.*