Assessment of Potato Mother Tuber Vigour Using the Method of Accelerated Ageing

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Abstract: The vigour of seed material determines the seed’s future productivity. Although there are several tests for determining seed vigour, there is a lack of standardization for the vegetative forms of seed material, including seed potatoes. We evaluated the vigour of mother tubers of 14 selected potato (Solanum tuberosum L.) cultivars using the method of accelerated ageing, that is, tubers were placed under conditions conducive to their physiological ageing from harvest to planting, in which the most important was the appropriate temperature (18ºC). The decrease in yield caused by such treatment in relation to the optimal storage conditions is a measure of vigour. As traits of tuber ageing, we evaluated the ways in which mother tubers sprouted, the lack of emergence on the plots and yield reduction in the mother tubers subjected to conditions conducive to physiological ageing from harvest to planting. The assessment of vigour was presented on a 9-point scale for relative yield. There were 3 cultivars that maintained high growth vigour of seed tubers while ageing in the light (mark 9) and 4 cultivars ageing in darkness (mark 8). The vigour of potato mother tubers was not correlated with either the length or mass of sprouts, or the percentage of sprouting eyes, nor was it correlated with the duration of the crop cycle of the individual cultivars. Application of this method allows potato cultivars to be characterized in the same way, regardless of the year of research and the set of cultivars being evaluated.

Key words: Accelerated ageing, Physiological ageing in darkness, Physiological ageing in light, Vigour of mother tubers on 9-point scale.

The vigour of potato mother tubers and seeds of different plant species is the sum of the properties that determine their physiological potential for rapid and uniform sprouting, full emergence and proper development of plants (Grzesiuk and Górecki, 1981). From the agricultural perspective it determines the seed material’s future productivity, which is a complex trait conditioned genetically, physiologically and ecologically. Therefore, three types of vigour are distinguished: genetic, physiological and ecological (Heydecker, 1972; Grzesiuk and Górecki, 1981). This classification of vigour indicates its distinct sources, but these forms are inseparable, and ultimately lead to the physiological result of a genetic programme in a changing environment.

Currently, there are several tests for determining vigour, but as yet they all relate to seeds (Dąbrowska et al., 2000). They can be divided into three groups: tests based on germination, including the modernized form based on a computer analysis of digital photographs of germinating plants (Sako et al., 2001; Oakley et al., 2004), physiological and biochemical tests (Marcos-Filho, 1998; Carvalho and Marcos-Filho, 2002) and complex tests (Grzywacz and Orzeszko-Rywa, 2007). Since 1950 more than 60 different tests have been proposed but the International Seed Testing Association (ISTA) Committee for Vigour Evaluation concentrated mainly on nine of them (Grzywacz and Orzeszko-Rywa, 2007); that is, growth tests, cold-test, cool-test, complex stress vigour test, Hiltner test, accelerated ageing test, controlled deterioration test, electric conductivity test and tetrazolium test.

At present ISTA is not involved in the standardization of the vegetative forms of seed materials, including potato mother tubers. However, this is a very important issue in agricultural practice because vigour is one of the major factors of potato mother tuber quality. The vigour of seed potatoes depends on their physiological age, thus on their physiological state influenced by chronological age and environmental conditions (Roztropowicz, 1985; Reust, 1986; Van der Zaag and Van Loon, 1987; Rykaczewska, 1993; Struik, 2007). Temperature and storage time, are the most important factors influencing the process of physiological ageing of tubers. Elevating the temperature during the autumn-to-spring storage period will accelerate the ageing process. Seed potatoes become physiologically older the longer the elapsed time since their initiation on the mother plant and the higher the ambient temperature.
Another factor accelerating this process is darkness (Reust, 1986). As the tubers age, their yield potential changes from initial increase to decrease after reaching the optimum (Perennec and Madec, 1980; Reust, 1982; Rykaczewska, 1993; Struik, 2007). In extreme cases, in which seed potatoes reach a too-advanced stage of development, after being planted in the field, progeny tubers may be produced directly on the mother tuber, without the phase of plant growth and development.

Low vigour of seed potatoes may be related with the high temperatures during the growing season, resulting in reduction of their natural rest (Susnoschi, 1981; Reust, 1982; Levy, 1985; Rykaczewska, 2004a, 2004b, 2004c). Low vigour may also be associated with the inability to ensure appropriate conditions during storage (temperature about 3°C, humidity 95% RH) (Czerko, 2007, 2009), which results in accelerated physiological ageing of tubers, early sprouting becomes common, and sometimes even the formation of small tubers on mother tubers (Rykaczewska, 1993), resulting in reduced vigour of seed tubers. Different vigour may also result from a potato seed of the same cultivar grown in different climatic regions (Reust, 1982). The response of individual cultivars, however, is diverse and is not closely related to the length of the dormancy period or the length of the growing season (Reust and Münster, 1975; Roztropowicz, 1985; Rykaczewska, 1993, 2010a, 2010b). This means that the early cultivars are not always characterized by a rapid rate of physiological ageing of tubers, or the late cultivars by a slow rate of ageing.

In this study, we evaluated the physiological vigour of mother tubers of 14 potato cultivars using the method of accelerated ageing (AA) which was established using the optimal conditions for potato seed storage (Struik and Wiersema, 1999) and conditions conducive to their physiological ageing (Reust, 1986) reported previously. Because the process of physiological ageing of potato tubers is promoted not only by higher temperature and humidity but also by darkness (Reust, 1986), we also investigated the effect of light on seed vigour of the tested cultivars.

**Materials and Methods**

The study was conducted in the years 2007/2008, and 2008/2009 at the Plant Breeding and Acclimatization Institute in the Research Division at Jadwisin (52°28'44"N and 21°02'38"E). The experimental objects were very early, early and medium early cultivars, a list of which is presented in Table 1. The seed potatoes for the study were produced in the northern region of Poland with the most favourable environmental conditions for their production. In the autumn of each year, just after harvest (October), certified seeds of the cultivars were divided into three batches. One of them was placed in a storage chamber under conditions optimal for seed potato storage (temperature of 3°C), whereas the other batches were subjected to conditions for accelerated ageing in light or darkness. The experimental objects were very early, early and medium early cultivars, a list of which is presented in Table 1. The seed potatoes for the study were produced in the northern region of Poland with the most favourable environmental conditions for their production.

![Table 1. List of tested cultivars.](image)

| No. | Cultivar | Maturity type | Year of registration | Company, country       |
|-----|----------|---------------|----------------------|------------------------|
| 1   | Arielle  | Very early    | 2006                 | Agrico, BA, Netherland |
| 2   | Berber   | Very early    | 2006                 | HZPC Netherland B.V.   |
| 3   | Justa    | Very early    | 2006                 | HZ Zamarte-Poland      |
| 4   | Milek    | Very early    | 2006                 | HZ Zamarte-Poland      |
| 5   | Bella Rosa | Early       | 2006                 | Europlant, Pflz-Germany|
| 6   | Eugenia  | Early         | 2006                 | HZ Zamarte-Poland      |
| 7   | Ewelina  | Early         | 2006                 | Europlant, Pflz-Germany|
| 8   | Latona   | Early         | 1997                 | HZPC Netherland B.V.   |
| 9   | Oman     | Early         | 2005                 | HZ Zamarte-Poland      |
| 10  | Owocja   | Early         | 2006                 | PMHZ Strzekcin-Poland  |
| 11  | Agnes    | Medium early  | 2005                 | Europlant, Pflz-Germany|
| 12  | Benek    | Medium early  | 2006                 | HZ Zamarte-Poland      |
| 13  | Elanda   | Medium early  | 2005                 | HZ Zamarte-Poland      |
| 14  | Folka    | Medium early  | 2003                 | Danespo A/S-Denmark    |

* Registration in the Polish National List of Varieties.
April 20th each year in an experimental field, on a poor clayey sand of a good agricultural suitability.

The field trials were set up in a randomized complete block design with four replicates. The size of the plots was 7.5 m$^2$, the number of plants per plot was 30 with 75 cm row spacing and 33 cm plant spacing. As a natural fertilizer we used a white mustard (*Sinapis alba* L.), plowed under after the first frost in autumn. Mineral fertilization was 90 kg N, 39 kg P and 112 kg K ha$^{-1}$. Crop pests and diseases were controlled as commonly done in the area. In late May, the blanks in the plots were counted and the lack of plant emergence was confirmed by unearthing and examining the mother tubers. The meteorological conditions during the growing seasons are given in Table 3.

On the last day of September when the crop cycle was completed, the plants were harvested using a potato elevator digger, without killing the vines. Yield and the relative yield in comparison with the Control were determined and expressed as a percentage. The decrease in yield caused by the AA treatments was used as a measure of the vigour of the mother tubers. A 9-point scale was used to measure the decrease in yield (Table 4). The results of the experiments were analyzed by ANOVA using a general linear model of statistics program in SAS Enterprise Guide 4 (SAS Institute, 2004). Means were separated by Tukey’s test at 5% p-value.

Table 2. Mother tuber treatments from autumn to planting.

| Treatment       | Procedure                                                                 |
|-----------------|---------------------------------------------------------------------------|
| Control         | Storage during whole storage period in a chamber under conditions optimal for potato seed (3ºC). Four weeks before the scheduled date of planting, pre-sprouting of mother tubers at the temperature 18ºC and high humidity (RH 85 – 90%) |
| AA-Light        | Pre-sprouting from autumn to planting in light in a chamber under conditions conducive to the physiological ageing of tubers (temperature 18ºC; RH 85 – 90%) |
| AA-Darkness     | Storage from autumn to spring in darkness in a chamber under conditions conducive to the physiological ageing of tubers (temperature 18ºC; RH 85 – 90%). Four weeks before the scheduled date of planting – tubers de-sprouting and next their pre-sprouting in light. |

Table 3. Precipitation and air temperature during growing season in the experimental field in the years of study.

| Year | Meteorological factor | Month | May | June | July | Aug. | Sep. |
|------|-----------------------|-------|-----|------|------|------|------|
|      | Precipitation (mm)    |       | 62.9| 43.5 | 68.8 | 80.9 | 48.8 |
|      | Deviation from average*(mm) |       | 10.9| –33.5| –4.2 | 18.9 | –2.2 |
| 2008 | Air temperature (ºC)  |       | 13.6| 17.1 | 18.1 | 17.6 | 11.6 |
|      | Deviation from average*(ºC) |       | 0.0 | 0.6  | –0.3 | –0.1 | –1.5 |
|      | Sielianinov coefficient ** |       | 1.64| 0.84 | 1.22 | 1.48 | 1.40 |
|      | Precipitation (mm)    |       | 80.8| 72.4 | 85.6 | 83.1 | 18.8 |
|      | Deviation from average*(mm) |       | 27.8| –3.6 | 12.6 | 25.1 | –30.2 |
| 2009 | Air temperature (ºC)  |       | 12.3| 17.3 | 21.3 | 17.3 | 14.2 |
|      | Deviation from average*(ºC) |       | –1.3| 0.9  | 2.9  | –0.5 | 1.1  |
|      | Sielianinov coefficient ** |       | 2.12| 1.38 | 1.28 | 1.54 | 0.44 |

* Average for 40 years
** Sielianinov hydrothermic coefficient: < 0.5, drought; 0.5 – 1.0, shortage; 1.1 – 2.0, wet; > 2.0, very wet.

Table 4. Scale of vigour assessment of potato mother tubers using the method of accelerated ageing (9: the best mark).

| Decrease in yield as the result of potato mother tubers storage under conditions of AA in relation to the control in % | Scale 1 – 9 |
|----------------------------------------------------------------------------------------------------------------|------------|
| ≤ 0                                                               | 9          |
| 0 – 10                                                            | 8          |
| 10 – 20                                                           | 7          |
| 20 – 30                                                           | 6          |
| 30 – 40                                                           | 5          |
| 40 – 50                                                           | 4          |
| 50 – 60                                                           | 3          |
| 60 – 70                                                           | 2          |
| 70 <                                                              | 1          |
Table 5. Mean squares, F value and significance level of tested factors – from the analysis of variance.

| Characteristics                  | Sources of variation |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
|----------------------------------|----------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|                                  | Cultivar             | Treatment | Year     | Interaction | Cultivar × Treatment |
|                                  | M.S. * | F  | Pr > F  | M.S. * | F  | Pr > F  | M.S. * | F  | Pr > F  | M.S. * | F  | Pr > F  |
| Mother tubers:                   |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| length of sprouts                | 9921    | 36.86   | <0.0001  | 285603  | 1061.13  | <0.0001  | 40      | 0.15 | 0.70  | 9356   | 34.76   | <0.0001  |          |          |          |          |          |          |
| length of spr. – cult. x AA-L    | 69      | 38.99   | <0.0001  | 1054    | 599.59   | <0.0001  | 0       | 0.01 | 0.92  | 11     | 6.33    | <0.0001  |          |          |          |          |          |          |
| length of spr. – cult. x AA-D    | 14587   | 37.32   | <0.0001  | 449111  | 1153.13  | <0.0001  | 30      | 0.08 | 0.78  | 13996  | 36.00   | <0.0001  |          |          |          |          |          |          |
| length of sprouts for Control    | 29      | 27.11   | <0.0001  | -       | -       | -       | 9       | 8.58 | 0.01  | -       | -       | -       |          |          |          |          |          |          |
| length of sprouts for AA-L       | 51      | 46.58   | <0.0001  | -       | -       | -       | 10      | 9.46 | 0.009 | -       | -       | -       |          |          |          |          |          |          |
| length of sprouts for AA-D       | 28554   | 35.73   | <0.0001  | -       | -       | -       | 116     | 0.15 | 0.70  | -       | -       | -       |          |          |          |          |          |          |
| mass of sprouts                  | 6       | 25.50   | <0.0001  | -       | -       | -       | 0       | 0.12 | 0.73  | -       | -       | -       |          |          |          |          |          |          |
| length of re-gr. sprouts         | 65      | 110.37  | <0.0001  | -       | -       | -       | 13      | 22.03| 0.004 | -       | -       | -       |          |          |          |          |          |          |
| % of sprouting eyes              | 126     | 1.92    | 0.13     | 8218    | 125.03   | <0.0001  | 1663    | 25.31| <0.0002| 42     | 0.64    | 0.78    |          |          |          |          |          |          |

Plants:

|                                  |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
|                                  | length of sprouts | -       | -       | -       | -       | -       | -       | -       | -       | -       | -       | -       |          |          |          |          |          |          |
|                                  | mass of sprouts   | -       | -       | -       | -       | -       | -       | -       | -       | -       | -       | -       |          |          |          |          |          |          |
|                                  | length of re-gr. sprouts | -       | -       | -       | -       | -       | -       | -       | -       | -       | -       | -       |          |          |          |          |          |          |
|                                  | % of sprouting eyes | -       | -       | -       | -       | -       | -       | -       | -       | -       | -       | -       |          |          |          |          |          |          |

Table 6. Length of sprouts depending on conditions of mother tuber treatment and year – group according to Tukey’s test.

| Conditions of mother tubers treatment | Cultivar | Group acc. Tukey’s test | Control Length of sprouts in mm | AA-Light Length of sprouts in mm | AA-Darkness Length of sprouts in mm |
|---------------------------------------|----------|-------------------------|----------------------------------|----------------------------------|-----------------------------------|
| Berber                                | 22       | a                       | Berber 30                        | 30                               | 30                                |
| Eugenia                               | 13       | b                       | Ewelina 24                       | 24                               | 24                                |
| Agnes                                 | 12       | bc                      | Eugenia 23                       | 23                               | 23                                |
| Evelina                               | 10       | bcd                     | Miełek 22                        | 22                               | 22                                |
| Bella Rosa                            | 10       | bcd                     | Agniesz 21                       | 21                               | 21                                |
| Latona                                | 10       | bcd                     | Arielle 19                       | 19                               | 19                                |
| Oman                                  | 9        | bcd                     | Bella Rosa 18                    | 18                               | 18                                |
| Elanda                                | 8        | cd                      | Justa 18                         | 18                               | 18                                |
| Miełek                                | 8        | cd                      | Folva 17                         | 17                               | 17                                |
| Arielle                               | 8        | d                       | Oman 16                         | 16                               | 16                                |
| Owacja                                | 8        | d                       | Benek 15                         | 15                               | 15                                |
| Benek                                 | 8        | d                       | Elanda 14                        | 14                               | 14                                |
| Folva                                 | 7        | d                       | Latona 12                        | 12                               | 12                                |
| Justa                                 | 7        | d                       | Owacja 12                        | 12                               | 12                                |

| 2008                                  | 10.4     | A                       | 2009 19.1                         | A                                | 2008 190.9                         | A                                |
| 2009                                  | 9.2      | B                       | 2008 17.9                         | B                                | 2009 186.9                         | A                                |
| Mean                                  | 9.8      | B                       | Mean 18.5                        | A                                | Mean 188.9                         | A                                |

Mean values followed by the same letters in the column of group acc. Tukey’s test are not significantly different at the 0.05 level.
Results

Highly significant impacts of the tested factors on the length of sprouts, the percentage of sprouting eyes, the lack of plant emergence, yield and relative yield were found (Table 5).

1. The length and mass of sprouts

The length of sprouts grown on mother tubers in the AA-Light treatment was on average almost twice as high as that in the Control, and in the AA-Darkness treatment it was nearly twenty times higher than in the Control (Table 6). However, the responses of cultivars to different treatments of mother tubers were varied. The very early cultivar Berber produced the longest sprouts in the Control and AA-Light treatments. In the dark the medium early ‘Agnes’ and early ‘Latona’ produced the longest sprouts. The shortest sprouts were: in the Control group the cultivars Justa, Folva, Benek, Owacja, Arielle; in the AA-Light treatment the cultivars Owacja and Latona; and in the AA-Darkness treatment the cultivars Justa, Elanda, Bella Rosa. There were no significant differences between the years of the study in the AA-darkness treatment. In other treatments, the differences were very small (1.2 mm). The mass of sprouts emerged in darkness before spring was largest in the cultivars Arielle, Berber, Milek, Eugenia and Agnes, and was closely related to their length (Table 7). The tubers of the tested cultivars had the ability to regenerate sprouts. The cultivar Owacja had the greatest ability in its regeneration. The length of re-growing sprouts was only slightly greater in 2008 than in 2009, but the differences were statistically significant.

2. The percentage of sprouting eyes

There was no significant difference in percentage of sprouting eyes among cultivars, and their interactions with the mother tuber treatment (Table 5). The percentage of sprouting eyes was lower in the AA-light than in the Control (Table 8). It was also lower in 2008 than in 2009.

3. Appearance of mother tubers just before planting

Fig. 1 shows a picture of mother tubers just before planting of six cultivars, two from each group of maturity type (Fig. 1). Their response to the different treatments in the period from autumn until planting is evident. Tubers in the AA-Light treatment have longer and more branching sprouts and then those in the Control. The tubers in the AA-Darkness treatment show an ability to regenerate sprouts and the decline of apical dominance. The cultivar Agnes appears to be the most tolerant to the treatments due to very slow physiological ageing of the tubers and the continuing apical dominance until spring.

4. Lack of plant emergence

A lack of emergence was observed in the mother tubers stored under AA conditions due to poor vigour (Table 9). The failure rate was the highest in the plots with the cultivar Eugenia in both treatments, and in cultivars Ewelina and Arielle in the AA-Darkness treatment. However, most of the cultivars showed full emergence or only a very small percentage of missing plants. There were no significant differences between the years (Table 5).

5. Yield

The yield varied with the year of the study (Table 10). It was higher in 2009 than in 2008 probably due to the more
abundant rainfall during the growing season particularly in May, June and July (see Table 3). The largest yield differences between years was observed in the cultivar Owacja. The decrease in yield was significantly greater in the AA-Darkness treatment than in the AA-Light treatment, in both years, but in the AA-Darkness treatment the difference between years was slightly smaller. No significant interaction of the mother tuber treatments with the cultivars was found (see Table 5). This means that the responses of the tested cultivars to tuber treatment were similar.

6. Relative yield

The relative yield (relative to control) of the tested cultivars significantly varied with the treatment of mother tubers (Table 5 and 11). It was lower in the AA-Darkness than in AA-Light treatment. A significant interaction of the mother tuber treatments with the cultivars was found. The relative yield in the AA-Light treatment was highest in Owacja and Elanda and that in the AA-Darkness treatment was highest in Agnes and Bella Rosa. The relative yield significantly varied with the year, but the difference was less than 2% on the average.

7. Assessment of the vigour of mother tubers using a 9-point scale

There was no significant correlation between the relative decrease in yield and the various parameters of sprouting of mother tubers, nor between the relative decrease in yield and the lack of plant emergence (Table 12). The vigour was therefore determined by the established methodology (Rykaczewska, 2010 b), using a 9-point scale (Table 4). Tuber vigour of the 14 tested cultivars was very high independent of their maturity type (Table 13). The vigour in the AA-Light treatment was highest in the cultivars Owacja (early), and Elanda and Folva (medium early), while that in the AA-Darkness treatment was highest in the cultivars Bella Rosa, and Owacja (early), and Agnes and Elanda (medium early).
Table 9. Lack of plant emergence of tested cultivars caused by week vigour of mother tubers stored under conditions of accelerated ageing in light and in darkness.

| Cultivar | Lack of plant emergence in % | AA-Light | Group ac. Tukey’s test | AA – Darkness | Group ac. Tukey’s test |
|----------|-------------------------------|----------|------------------------|---------------|------------------------|
| Eugenia  | 11.6                          | a        |                        | Eugenia       | 14.2                   | a                      |
| Justa    | 2.5                           | b        |                        | Ewelina       | 8.4                    | b                      |
| Ewelina  | 2.5                           | b        |                        | Arielle       | 8.3                    | b                      |
| Latona   | 2.3                           | b        |                        | Latona        | 3.8                    | bc                     |
| Arielle  | 1.6                           | bc       |                        | Benek         | 3.4                    | c                      |
| Agnes    | 0.2                           | bc       |                        | Justa         | 2.5                    | c                      |
| Milek    | 0.2                           | bc       |                        | Oman          | 1.6                    | c                      |
| Berber   | 0.0                           | c        |                        | Berber        | 0.8                    | c                      |
| Folva    | 0.0                           | c        |                        | Agnes         | 0.4                    | c                      |
| Elanda   | 0.0                           | c        |                        | Milek         | 0.4                    | c                      |
| Bella R. | 0.0                           | c        |                        | Bella Rosa    | 0.0                    | c                      |
| Benek    | 0.0                           | c        |                        | Elanda        | 0.0                    | c                      |
| Oman     | 0.0                           | c        |                        | Folva         | 0.0                    | c                      |
| Owacja   | 0.0                           | c        |                        | Owacja        | 0.0                    | c                      |
| Mean     | 1.5                           | B        |                        | Mean          | 3.1                    | A                      |

Mean values followed by the same letter in the column of group acc. Tukey's test are not significantly different at the 0.05 level.

Table 10. Yield (t ha⁻¹) of tested cultivars depending on mother tuber treatment from autumn to planting (see Table 2).

| Cultivar | Treatment | Year | Mean |
|----------|-----------|------|------|
|          | Control   | 2008 | 2009 |
|          | AA-Light  |      |      |
|          | AA-Darkness |     |      |
| Arielle  | 41.96     | 30.67| 45.18|
| Berber   | 35.08     | 26.07| 31.76|
| Justa    | 43.83     | 30.30| 48.52|
| Milek    | 42.33     | 31.05| 48.37|
| Bella R. | 35.89     | 28.15| 41.49|
| Eugenia  | 39.75     | 27.08| 44.78|
| Ewelina  | 31.84     | 25.00| 34.89|
| Latona   | 41.69     | 34.07| 42.50|
| Oman     | 41.30     | 33.33| 39.11|
| Owacja   | 53.66     | 38.54| 66.22|
| Agnes    | 51.23     | 41.74| 59.17|
| Benek    | 51.20     | 40.13| 55.56|
| Elanda   | 56.26     | 50.03| 60.15|
| Folva    | 55.03     | 45.24| 59.54|
| Mean     | 44.36 A   | 34.39 B| 48.37 A| 41.38 |
|          | 2008      | 36.49 A| 32.04 C|
|          | 2009      | 52.22 A| 49.16 B| 43.72 C|

Mean values followed by the same letter are not significantly different at the 0.05 level by Tukey’s test.
### Table 11. Relative yield of tested cultivars depending on mother tuber treatment – in % in relation to the Control.

| Cultivar     | Relative yield treatment | Decrease in the relative yield treatment |
|--------------|--------------------------|------------------------------------------|
|              | Control | AA-Light | AA-Darkness | Mean | AA-Light | AA-Darkness |
| Arielle      | 100.0   | 90.0 abc | 83.6 ab     | 91.2 abc | 10.0 | 16.4 |
| Berber       | 100.0   | 78.0 c   | 69.2 b      | 82.4 d   | 22.0 | 30.8 |
| Justa        | 100.0   | 89.6 abc | 79.9 ab     | 89.8 bcd | 10.4 | 20.1 |
| Milek        | 100.0   | 95.7 abc | 87.7 ab     | 93.8 abc | 6.3  | 12.5 |
| Bella Rosa   | 100.0   | 99.5 ab  | 92.9 a      | 97.5 ab  | 0.5  | 7.1  |
| Eugenia      | 100.0   | 90.7 abc | 80.8 ab     | 90.5 abcd| 9.3  | 19.2 |
| Ewelina      | 100.0   | 97.9 ab  | 85.2 ab     | 94.3 abc | 2.1  | 14.8 |
| Latona       | 100.0   | 90.2 abc | 85.6 ab     | 91.9 abc | 9.8  | 14.4 |
| Oman         | 100.0   | 86.2 bc  | 77.8 ab     | 88.0 cd  | 13.8 | 20.2 |
| Owacza       | 100.0   | 103.9 a  | 90.9 ab     | 98.2 a   | +3.9 | 9.1  |
| Agnes        | 100.0   | 99.0 ab  | 95.1 a      | 98.0 a   | 1.0  | 4.9  |
| Benek        | 100.0   | 91.9 abc | 88.6 ab     | 93.5 abc | 8.1  | 11.4 |
| Elanda       | 100.0   | 102.8 a  | 91.7 ab     | 98.2 a   | +2.8 | 8.3  |
| Folva        | 100.0   | 101.6 ab | 85.0 ab     | 95.5 abc | +1.6 | 15.0 |
| Mean         | 100.0 A | 93.9 B   | 85.3 C      | 93.1     | 6.1  | 14.7 |
| 2008         | 100.0 A | 94.5 B   | 87.3 C      | 93.9 a   | 5.5  | 12.7 |
| 2009         | 100.0 A | 93.3 B   | 83.3 C      | 92.2 b   | 6.7  | 16.7 |

### Table 12. Correlation coefficients between investigated features of mother tubers and relative yield.

| Investigated features                                      | Relative yield in the treatment |
|------------------------------------------------------------|---------------------------------|
|                                                            | AA-Light | AA-Darkness |
| Length sprouts in the Control                              | −0.66     | −0.56       |
| Length of sprouts in the AA-Light treatment                | −0.53     | −0.49       |
| Length of sprouts in the AA-Darkness treatment             | −0.23     | +0.01       |
| Length of regrowing sprouts in the AA-Darkness treatment   | +0.51     | +0.40       |
| Mass of de-sprouted sprouts / tuber                        | −0.41     | −0.19       |
| % of sprouted eyes in the AA-Light treatment               | −0.24     | −0.34       |
| % of sprouted eyes in the Control                          | −0.11     | −0.06       |
| Lack of plant emergence AA-Light                           | −0.18     | −0.24       |
| Lack of plant emergence AA-Darkness                        | −0.25     | −0.26       |

### Table 13. Assessment of the vigour of potato mother tubers after storage from autumn to spring under conditions of accelerated ageing in light and darkness - using a 9-point scale (see Table 4).

| Cultivar     | very early | early | medium early |
|--------------|------------|------|--------------|
| name         | AA-Light   | AA-Darkness | AA-Light | AA-Darkness |
| Arielle      | 8          | 7    |              |
| Berber       | 6          | 5    |              |
| Justa        | 7          | 6    |              |
| Milek        | 8          | 7    |              |
| Bella Rosa   | 8          | 8    |              |
| Eugenia      | 8          | 7    |              |
| Ewelina      | 8          | 7    |              |
| Elanda       | 8          | 7    |              |
| Latona       | 8          | 7    |              |
| Oman         | 7          | 6    |              |
| Owacza       | 9          | 8    |              |
| Agnes        | 8          | 8    |              |
| Benek        | 8          | 7    |              |
| Elanda       | 9          | 8    |              |
| Folva        | 9          | 7    |              |
Discussion

1. Sprouting of potato mother tubers and plant growth

Varied sprouting of potato mother tubers, under different storage conditions, was associated with their physiological age as reported previously (Perennec and Madec, 1980; Hartmans and Van Loon, 1987; Van der Zaag and Van Loon, 1987; Rykaczewska, 1993, 1999, 2000; Van Ittersum et al., 1993; Struik, 2007). Temperature, together with storage time, are the most important factors, influencing the process of physiological ageing of tubers. In the autumn-to-spring storage period, the longer the time elapsed after the initiation of sprouts on the mother plant and the higher the ambient temperature, the more accelerated the ageing process. Another factor accelerating this process is darkness (Reust, 1986). In a previous study, the dormancy period of tubers was shortened by placing in darkness for 1 to 17 days (Rykaczewska, 1983). As physiological ageing progresses, the seed tuber goes through different stages, including dormancy (no sprouts), apical dominance (only one sprout), normal sprouting (a few sprouts per seed tuber), advanced sprouting (many sprouts per seed tuber, which are often branched), senility (excessive sprouting with very week sprouts) and incubation period (little tuber formation) (Van der Zaag and Van Loon, 1987; Rykaczewska, 1993; Struik, 2007). This was partly confirmed in the present studies by the attached photographs (Fig. 1) and the results on the percentage of sprouted eyes.

Earlier studies (Rykaczewska, 1999; Struik, 2007) showed that breaking off the sprouts before planting could additionally reduce the vigour of mother tubers. For this reason, an important element of the methodology is to break off the sprouts a month before planting, and then re-sprouting the tubers. The length of sprouts in the Control combination in this study was optimum which is recommended for potato producers (Rykaczewska, 1997a, 1997b). However, in the cultivar Berber the sprouts were more than twice as great as the other cultivars, which indicates that in practice, mother tubers of this cultivar should be pre-sprouted at a lower temperature, to slow down the process of physiological ageing. In this study there was no impact of year on either length or mass of sprouts, but the length of re-growing sprouts and percentage of sprouting eyes varied with the year. The length of re-growing sprouts was 2.5 mm shorter in 2008 than in 2007 but with practically no significance. However, a larger percentage of sprouting eyes in 2009 than in 2008 pointed to a different physiological age of the seed material in the years of study. This is explained to have resulted from changing environmental conditions in the areas of seed production. This has already been shown in previous works (Roztropowicz, 1985; Rykaczewska, 1993). A lower percentage of sprouting eyes in the AA-Light treatment was associated with the persistence of apical dominance in the tubers subjected to sprouting in the autumn, while a higher percentage in the Control was caused by a later start of sprouting, during the waning of apical dominance. In our experiment, after planting the mother tubers in the field, rather surprising was full or nearly full plant emergence in most cultivars in all treatments. The phenomenon where seed potatoes reached too advanced a stage of development, and progeny tubers were produced directly on the mother tuber, without the phase of plant growth and development, was observed mainly in the early cultivar Eugenia. The impact of maturity type on the lack of full plant emergence was not found. The percentage of plant emergence in the plots of the AA-Light and AA-Darkness treatments was only a symptom of seed vigor.

In a previous work (Rykaczewska, 2010a), the vigour of tubers was assessed for 24 cultivars. The length and mass of stems and leaf area index were then measured. However, due to high labor intensity and lack of correlation of these traits with the vigour of potato tubers, these indicators are not included in the current study. Generally, the shorter length and smaller mass of the stems and the lower leaf area index seem to be typical for the plants growing from potato mother tubers that are physiologically older (Rykaczewska, 2002a, 2002b, 2010a).

2. Yield and assessment of the seed vigour of potato cultivars

In the present method of assessing potato mother tuber vigour, the measure can only be the relative yield in relation to the Control. Other indicators, such as the sprouting of tubers are merely symptoms of physiological age and vigour of tubers. Evaluation of potato mother tuber vigour on the basis of plant development may not be sufficient because the cultivars characterized by full emergence varied considerably in terms of relative yield, and those, characterized by a lack of full emergence showed relatively small decreases in yield as compared to the Control. In the work of Roztropowicz et al. (1983) 1% failure of plants caused a 0.6% decline in average yield. This was most likely related to better use of available nutrients and light. In our study, the lack of a strict relationship between plant emergence rate and relative yield was confirmed by the correlation coefficient, which had very low values.

A very important problem is the varied response of individual cultivars to the same factors that modify the physiological age of mother tubers (Reust and Münster, 1975; Rykaczewska, 1987a, 1987b; Van Loon, 1987; Caldiz et al., 2001). Therefore, measures and indicators of the physiological age of tubers have been explored. One of these measures is the accumulated degree-days (O’Brien et al., 1983; Struik et al., 2006; Struik, 2007). In many cases,
this indicator is very useful; however, as shown previously (Rykaczewska, 1987a, 1987b), it is not a universal measure, because the same sum of temperatures accumulated in autumn and in spring have different effects on plant growth and yield of potato. Struik et al. (2006) also found that the effect of temperature sum during storage had a different impact on seed age depending on whether warm temperatures occurred at the beginning or at the end of the storage period. Another measure under consideration in research work is the length of the incubation period (time elapsed from sprouting until new tuber formation on the sprouts) (Reust, 1986). Those studies were conducted mostly on only up to a dozen cultivars (Reust and Münster, 1975; Caldz et al., 2001). However, while analyzing a larger number, we sometimes find that the tops of the sprouts in some cultivars are dying off despite being provided with identical laboratory conditions, which can prolong the incubation period (Rykaczewska, 1993).

Indicators of the physiological age of potato tubers can also be biochemical. These include the content of sucrose, citric acid, malic acid (Reust and Aerny, 1985), the tetrazolinum test (Sacher and Iritani, 1982), and the electrolyte leakage test (De Weerd et al., 1995). These tests generally show some correlation only with the sprouting of tubers, not with the yield.

According to Struik (2007), the most important task in research on physiological age is to find a reliable and rapid diagnostic tool for assessing the rate of physiological ageing in various stages of mother tuber development and the ability to anticipate further ageing as a function of temperature. Many research teams have already undertaken this challenge, but finding the features that could assess the physiological status of tubers of a cultivar in different environmental conditions and predicting future trends are too difficult. It seems that the application of modern molecular methods could help to assess this physiological property of tubers in different storage conditions. These tools will also help in the optimization of seed vigour depending on the type and location of cultivation. However, with the current lack of proper molecular methods, it was proposed to assess the vigour of tubers of different cultivars using a laboratory (Rykaczewska, 1993) or field method (Rykaczewska, 2003, 2004d). The laboratory method is very simple as it is based on the assessment of the maximum intensity of sprouting in successive months of storage. However, to be able to use this method, it is necessary to have an air-conditioned laboratory maintained at a constant temperature and relative humidity. In addition, its drawback is the inability to refer the test results to the yield. This can be achieved using the field method of assessment.

The method we used for assessing the vigour of potato seed tubers is analogous to the AA test, recognized by the International Seed Testing Association as a standard method for the evaluation of soybeans (Glycine max (L.) MERR) (Grzywacz and Orzeszko-Rywka, 2007). In this test, seeds are exposed to two stress factors: high temperature and high air humidity. Its modified version for small seeds of other plant species is an accelerated ageing test in a saturated salt solution (SSAA) (Rodo and Marcos-Filho, 2003; Contreras and Bardos, 2005) and a controlled deterioration test (CD) (Marcos-Filho, 1998; Dąbrowsk et al., 2000; Rodo and Marcos-Filho, 2003; Grzywacz and Orzeszko-Rywka, 2007).

The use of the method of AA for seed tubers allowed the evaluation rate of physiological ageing to be evaluated in 14 potato cultivars. Generally this method allows the assessment of potato mother tubers vigour of different cultivars, regardless of their physiological age, which is not measurable. The application of a 9-point scale according to the established methodology does not refer to the absolute yield, but to the relative yield, so that the method becomes universal. By means of this method it is possible to characterize one cultivar only or several cultivars at the same time. The present study reconfirmed the previous report (Rykaczewska, 2010a) that the national gene pool currently contains more potato cultivars with a slow rate of physiological ageing of tubers than it did in the 1980s (Rykaczewska, 1987a). An additional confirmation of these conclusions is provided by the results of the analysis of the length of the dormancy period of all the Polish cultivars bred in the years 1955 – 1994, which shows a clear increase in the number of cultivars with a long dormancy period and a reduction in the number of cultivars with a short dormancy period (Rykaczewska, 1997c).

Conclusion

The mode and intensity of sprouting of potato mother tubers in the period from harvest to spring are not unambiguous indicators of their vigour. The method of AA and the use of a 9-point scale for assessing the vigour of potato mother tubers allows characterization of potato cultivars in the same way, regardless of the time of research and the set of the genotypes. The assessment may cover multiple cultivars. Most of the potato cultivars registered recently in the Polish directory of cultivars are characterized by slow physiological ageing of seed potatoes, and therefore by their high physiological vigour. Seed potatoes of cultivars with high vigour after exposure to accelerated ageing in the light can be pre-sprouted for a longer period without fear of a significant loss in their yielding potential. Cultivars with high vigour of mother tubers, despite having been subjected to accelerated ageing in darkness, can be successfully used on farms that do not have modern storage facilities.

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References

Caldiz, D.O., Fernández L.V., Struijk, P.C. 2001. Physiological age index: a new, simple and reliable index to assess the physiological age of seed potato tubers based on haulm killing date and length of the incubation period. *Field Crop. Res.* 69: 69-79.

Carvalho, M.V., Marcos-Filho, J. 2002. Potassium leakage and maize seed physiological potential. *Sci. Agric.* 59: 315-319.

Contreras, S., Barros, M. 2005. Vigour tests on lettuce seeds and their correlation with emergence. *Cienic Investig Agrar.* 32: 3-10.

Czerko, Z. 2007. Losses in potato tubers stored in a storehouse with or without a humidification system. *Bul. IHAR.* 24: 245-250*.

Czerko, Z. 2009. The influence of potato cultivar and storage temperature on the amount of losses in tuber mass. *Bul. IHAR.* 25: 159-168*.

Dąbrowska, B., Pokojska, H., Suchorska-Tropilo, K. 2000. In University of Life Sciences ed., Methods of laboratory seed evaluation. SGGW, Warsaw. 1-111**.

De Weerd J.W., Hiller L.K., Thomton, R.E. 1995. Electrolyte leakage of aging potato tubers and its relationship with sprouting capacity. *Potato Res.* 38: 257-270.

Grzesiuk, S., Górecki, R.J. 1981. Seed vigor as a new criterion for the value of seed and methods of its determination. *Adv. Agric. Sci.* 6: 39-56*.

Grzywacz, P., Orzeszko-Rywka A. 2007. Traditional and modern methods of seed vigour testing. *Adv. Agric. Sci.* 5: 79-80*.

Hartmans, K.J., Van Loon, C.D. 1987. Effect of physiological age on growth vigour of seed potatoes of two cultivars. Influence of storage period and temperature on sprouting characteristics. *Potato Res.* 30: 397-409.

Heydecker, W. 1972. Vigour. In E.H. Roberts ed., Viability of Seeds. Chapman and Hall, London: 209-252.

ISTA. 2011. Chapter 5. In The International Seed Testing Association ed., International Rules for Seed Testing. Bassersdorf, Switzerland. 5-53.

Kolasińska, K., Maluszynska E. 2002. 26th Congress of the International Seed Testing Association – ISTA, Angers, France, 2001. *Bull. IHAR* 221: 253-256*.

Levy, D. 1985. The response of potatoes to a single transient heat or drought stress imposed at different stages of tuber growth. *Potato Res.* 28: 415-424.

Marcos-Filho, J. 1998. New approaches to seed vigour testing. *Sci. Agric.*, *Pracidaba*, 55 (Special Issue): 27-33.

Oakley, K., Kester, S.T., Geneve, R.L. 2004. Computer-aided digital image analysis of seedling size and growth rate for assessing seed vigour in impatient. *Seed Sci. Tech.* 32: 837-845.

O’Brien, P.J., Allen, E.J., Bean, J.N., Griffith, R.J., Jones, S.A., Jones, J.L. 1983. Accumulated day-degrees as a measure of physiological age and the relationship with growth and yield in early potato varieties. *J. Agric. Sci.* 101: 613-631.

Perennec, P., Madec, P. 1980. Physiological age of potato tubers. Impact on sprouting and repercussion on the behavior of plants. *Potato Res.* 23: 183-198***.

Reust, W., Münster, W. 1975. The incubation period of potato cultivars of Switzerland assortment and its importance. *Rev. Suisse Agric.* 7: 185-187***.

Reust, W. 1982. Contribution to the appreciation of the physiological age of potato tubers (*Solanum tuberosum L.*) and study of its importance on performance. Dr. Thesis ETH., Switzerland. 1-114***.

Reust, W., Aerny, J. 1985. Determination of physiological age of potato tubers with using sucrose, citric and malic acid as indicators. *Potato Res.* 28: 251-261.

Reust, W. 1986. EAPR Working Group Physiological age of the potato. *Potato Res.* 29: 268-271.

Rodo, A.B., Marcos-Filho, J. 2003. Accelerated aging and controlled deterioration for the determination of the physiological potential of onion seeds. *Sci. Agric.* 60: 465-469.

Roztropowicz, S., Rykaczewska, K., Mikolajko, B. 1983. Relationship between yield and percentage of blanks on potato crop (model experiment). *Bull. Potato Inst.* 29: 63-71*.

Roztropowicz, S. 1985. The importance of physiological age of tuber in the plant development and productivity. In W. Gabriel ed., Potato Biology. PWN, Warszawa. 104-119**.

Rykaczewska, K. 1983. Length of dormancy in tubers of early potato cultivars differing in physiological age. *Bull. Potato Inst.* 29: 117-128*.

Rykaczewska, K. 1987a. The effect of physiological age of mother tubers differentiated by autumn and spring pre-sprouting on growth and yielding of early potato cultivars. *Ziemniak, Kartofel, The Potato*, 1986 / 1987: 17-38*.

Rykaczewska, K. 1987b. The effect of chronological age of seed early potato cultivars on its biological value. *Ziemniak, Kartofel, The Potato*, 1986 / 1987: 39-49*.

Rykaczewska, K. 1993. Physiological age of potato mother tubers as a factor modifying plant productivity. *Fragm. Agron.* 2: 5-50*.

Rykaczewska, K. 1997a. Pre-sprouting of potato seeds. Potato production. Technology - Economics - Marketing. Red. J. Chodkowski, IHAR Bonin 1997: 85-88**.

Rykaczewska, K. 1997b. Ways of dealing with seeds, to preserve the potential of yielding. Potato production. Technology - Economics - Marketing. Red. J. Chodkowski, IHAR Bonin 1997: 27-34**.

Rykaczewska, K. 1997c. Dormancy period of potato tubers of cultivars bred in the years 1955-1994. *Bull. Potato Inst.* 48: 59-64*.

Rykaczewska, K. 1999. Effect of physiological age of mother tubers and de-sprouting before planting on plant growth and yield of early potato cultivars. *Bull. IHAR* 209: 97-110*.

Rykaczewska, K. 2000. Effect of physiological age of seeds on tuber size in the yield of early potato cultivar. *Bull. IHAR* 215: 265-276*.

Rykaczewska, K. 2002a. The role of physiological age of mother tubers in the formation of canopy architecture and yield of potato. Part I. Effect on plant structure and architecture of the canopy. *Bull. IHAR* 223 / 224: 267-280*.

Rykaczewska, K. 2002b. The role of physiological age of mother tubers in the formation of canopy architecture and yield of potato. Part II. Impact on yield and its structure. *Bull. IHAR* 223 / 224: 281-290*.

Rykaczewska, K. 2003. Evaluation of the rate of physiological aging of
seed potatoes by field method. *Fragm. Agron.* 3: 65-74*.

Rykaczewska, K. 2004a. Effect of high temperature during vegetation on potato yield, tuber dormancy and seed tuber yielding ability. I. Plant development and yield. *Adv. Agric. Sci.* 496: 185-198*.

Rykaczewska, K. 2004b. Effect of high temperature during vegetation on potato yield, tuber dormancy and seed tuber yielding ability. II. Tuber dormancy duration. *Adv. Agric. Sci.* 496: 197-206*.

Rykaczewska, K. 2004c. Effect of high temperature during vegetation on potato yield, tuber dormancy and seed tuber yielding ability. III. Value of seed tuber yielding. *Adv. Agric. Sci.* 496: 207-216*.

Rykaczewska, K. 2004d. Response of early and very early cultivars to physiological age of potato mother tubers - evaluation by field method. *Adv Agric Sci.* 497: 551-560*.

Rykaczewska, K. 2010a. The effect of stress conditions during storage period on the vigour of potato mother tubers. *Fragm. Agron.* 27: 117-127*.

Rykaczewska, K. 2010b. The effect of high temperature during storage on the vigour of potato mother tubers. *Potato Res.* 53: 325-329.

Sacher, R.F., Iritani, W.M. 1982. Tetrazolium tests as indicators of tuber physiological age and yield potential. *Am. J. Potato Res.* 59: 613-625.

Sako, Y., McDonald, M.B., Fujimura, K., Evans, A.F., Bennett, M.A. 2001. A system for automated seed vigour assessment. *Seed Sci. Technol.* 29: 625-636.

SAS Institute Inc. 2004. SAS. 9.1. Companion for Windows. SAS Publishing, Cary, NC, USA.

Struik, P.C., Wiersema, S.G. 1999. Seed Potato Technology. Wageningen Accademic Pub. Wageningen, The Netherlands. 1-383.

Struik, P.C., Van der Putten, P.E.L., C Eldiz, D.O., Scholte, K. 2006. Response of stored potato seed tubers from contrasting cultivars to accumulated day-degrees. *Crop. Sci.* 46: 1156-1168.

Struik, P.C. 2007. The canon of potato science: 40. Physiological age of seed tubers. *Potato Res.* 50: 375-377.

Susnoschi, M. 1981. Seed potato quality as influenced by high temperatures during the growth period. 1. Effect of storage temperature on sprout growth. *Potato Res.* 24: 371-379.

Van der Zaag, D.E., Van Loon, C.D. 1987. Effect of physiological age on growth vigour of seed potatoes of two cultivars. 5. Review of literature and integration of some experimental results. *Potato Res.* 30: 451-472.

Van Ittersum, M.K., Scholte, K., Warshavsky, S. 1993. Advancing growth vigor of seed potatoes by a haulm application of gibberellic acid and storage temperature regimes. *Am. J. Potato Res.* 70: 21-34.

Van Loon, C.D. 1987. Effect of physiological age on growth vigour of seed potato of two cultivars. 4. Influence of storage period and storage temperature on growth and yield in the field. *Potato Res.* 30: 441-450.

* In Polish with English summary.

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