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Effect of storage time on antioxidant content in seeds of agricultural plants

Вплив тривалості зберігання на вміст антиоксидантів у насінні сільськогосподарських рослин

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Abstract

This study investigated the impact of storage time on the prooxidant-antioxidant balance (PAB) in seed tissues of 12 agricultural plant species, including both monocots and dicots. We measured superoxide generation, TBA-active products, and the activity of enzymatic antioxidants (superoxide dismutase, catalase, and cytochrome oxidase) and non-enzymatic antioxidants (ascorbic acid and glutathione). Biochemical parameters were recorded monthly for one year.

Our results demonstrated that the activity of enzymatic antioxidants and the content of non-enzymatic antioxidants decreased with increased seed storage time. Conversely, both the generation of reactive oxygen species and the level of free radical damage to biomolecules increased. The percentage change in free radical peroxidation and

Анотація

У цьому дослідженні вивчався вплив терміну зберігання на прооксидантно-антиоксидантний баланс (ПАБ) у тканинах насіння 12 видів однодольних та дводольних сільськогосподарських рослин. Визначали рівень генерації супероксиду, вміст ТБК-активних продуктів, активність ферментативних (супероксиддисмутази, каталази, цитохромоксидази) та низькомолекулярних антиоксидантів (аскорбінової кислоти та глутатіону). Біохімічні показники реєстрували щомісяця протягом року.

У результатах наших досліджень показано, що активність ферментативних антиоксидантів і вміст низькомолекулярних антиоксидантів знижувалися зі збільшенням терміну

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antioxidant protection depended on the initial PAB status of the seeds. Monocots exhibited a greater overall increase in prooxidant activity during storage, while dicots showed a less pronounced decrease in antioxidant content. A notable surge in prooxidant activity and a corresponding decline in antioxidant activity occurred at 9-10 months of storage for dicots and 6-7 months for monocots. These findings highlight the importance of considering storage time and species-specific differences to optimize planting strategies and seed care, as well as the use of appropriate plant foods.

Keywords: prooxidants, antioxidants, ascorbic acid, catalase.

зберігання насіння. Тоді ж як утворення активних форм Оксигену та вільнорадикальне пошкодження біомолекул зросли. Відсоткова зміна вільнорадикального перекисного окислення та антиоксидантного захисту залежала від початкового ПАБ-статусу насіння. Дослідні однодольні рослини показали більше загальне збільшення прооксидантної активності під час зберігання, тоді як дводольні продемонстрували менш виражене зниження вмісту антиоксидантів. Помітний стрибок прооксидантної активності та відповідне зниження антиоксидантного захисту спостерігався на 9-10 місяці зберігання для дводольних та на 6-7 місяці для однодольних. Ці висновки підкреслюють важливість урахування часу зберігання та видоспецифічних відмінностей для оптимізації стратегії посадки та догляду за насінням, а також вживання відповідних рослинних продуктів харчування.

Ключові слова: прооксиданти, антиоксиданти, аскорбінова кислота, каталаза.

Introduction

Antioxidants (AOs) are biologically active natural protectors of our body that promote adaptation to stressful conditions and changing environment, accompany normal growth and development processes, inhibit aging processes, promote regeneration and recovery from diseases and disorders, help to get out of the prodromal period into the state of homeostasis, and are natural antimutational agents (Marrocco et al., 2017; Kohen & Nyska, 2002; Halliwell, 2006). Our body synthesises its own AOs and replenishes their reserves from plant and animal origin products, and the content of AOs even in the healthiest food significantly depends on the conditions and duration of the storage (Xu et al., 2017; Song et al., 2010; Shao et al., 2008). A decrease in the content of AOs in the body leads to an increase in the amount of prooxidants (POs), represented by reactive Oxygen species (ROS), other free radicals and their transformation products (Pacheco et al., 2018). According to numerous scientific studies, the primary cause of diseases at the molecular level is damage to biopolymers. For example, ROS cause the formation of free radicals that trigger chain reactions of protein damage, the creation of interstrand cross-links, which makes DNA incapable of transcription and replication, and, in turn, makes normal cell division and protein biosynthesis impossible (Scandalios, 2002; Van Breusegem & Dat, 2006). Damage to the integrity of cell organelle membranes and plasma membrane is the first cytological indicator of most diseases (Dickinson, 2003). Free radicals cause peroxidation of membrane lipids, creation of intermolecular cross-links of fatty acid fragments, which changes the balance of membrane viscosity and fluidity and disrupts its transport properties. An increase in the content of free radicals leads to the destruction of biologically active substances synthesised by our body and obtained from food, which leads to a decrease in the nutritional value of food, its metabolic capacity, and therefore its benefits (Rampon et al., 2018; Rhoads et al., 2006; Apel & Hirt, 2004; Foyer & Noctor, 2009; Janků et al., 2019; Mittler, 2017). The imbalance of the prooxidant-antioxidant system (PAS) in seed tissues leads to a decrease in germination, which in turn leads to unnecessary costs for seed procurement, irrational use of sown areas and extensive farming (Bartoli et al., 2013; Oracz & Karpinski, 2016; Kumar et al., 2011) to take into account the storage time of plant products when planning a diet. For example, our previous studies have shown that soaking seeds leads to the initiation of germination processes and an increase in the level of AOs, but plant products that have been stored for a long time may contain very low baseline levels of AOs or not contain them at all. This devalues the benefits of whole grain products and so-called "live cereals", in the preparation of which pre-soaking and minimal heat treatment is recommended in order to preserve the maximum amount of biologically active substances in food. All of the above-mentioned enhances the relevance of the research topic and its significant practical importance for a wide range of readers and consumers.

The objective is to identify patterns of changes in the prooxidant-antioxidant balance in tissues depending on the storage time of plant products.

To achieve the objective, we identified the following tasks:

1) To study the change in the content of enzymatic AOs in plant tissues, depending on the storage period;
2) To determine the change in the content of low molecular weight AOs in plant tissues, depending on the storage period;
3) To experimentally confirm the change in the content of POs in plant tissues, depending on the storage period;
4) To determine the change in the content of free radical peroxidation products (FRP) of membranes in plant tissues, depending on the storage period;
5) To investigate changes in the activity of membrane markers of free radical peroxidation in plant tissues, depending on the storage period;
6) To trace the change in the balance of PAS links depending on the storage period of plant products;
7) To determine the species-specific features of the PAS state of experimental plants.

The article consists of the review of the literature, which provides an analysis of the works of advanced scientists in this direction, and highlights the components that require further research and systematization. In the methodology section, the principles of constructing the research scheme are given, the expediency of the choice of methods of analysis of each component of the state of the pro-oxidant-antioxidant system is substantiated, the conditions and repetition of the experiment are indicated. The analysis and generalization of the research results is maximally illustrated by graphs that reflect the dynamics of changes in the value of research indicators every month during the year, which is convenient for perception, visualizes the interspecies difference, and serves as a basis for conclusions, practical recommendations and prospects for further scientific research.

Literature Review

A number of leading scientists have studied the importance of POs and AOs (Halliwell, 2006; Shao et al., 2008; Pacheco et al., 2018; Scandalios, 2002; Apel & Hirt, 2004; Foyer & Noctor, 2009; Janků et al., 2019; Mittler, 2017). One of the top largest biochemical schools that regularly works in this area is the school of Nicholas Smirnoff (Smirnoff, 2005, 2019). Numerous achievements in PAS biochemistry in Ukraine are made by O.P. Dmytriyev, Z.M. Kravchuk, Y.E. Kolupaev, Y.V. Karpets, (Dmytriyev & Kravchuk, 2005; Kolupaev et al., 2019). Most scientists agree that the main enzymatic AOs are superoxide dismutase (SOD) (Berwal & Ram, 2019) and catalase, and low-molecular weight ascorbic acid (AA) and glutathione (GSH). The AOs properties of SOD are described in the works of Baiano A., del Nobile M.A., Berwal M.K., & Ram C. (Baiano & Nobile, 2016; Berwal & Ram, 2019), and catalase in the works of Nandi, A., Yan, L. J., Jana, C. K., & Das. (Nandi et al., 2019). The protective role of AA was investigated by Rietjens I.M., Boersma M.G., Haanm Ld., Spenkelink B., Awad H.M., Cnubben N.H., Padayatty S.J., Katz A., Wang Y., Eck P., Kwon O., Lee J.H., Chen S., Corpe C., Levine M., Dutta A., Paciolla S.; Fortunato, S.; Dipierro, N.; Paradiso, A.; De Leonardis S. (Rietjens et al., 2002; Padayatty et al., 2003; Paciolla et al., 2019).

Szalai G, Kellos T, Galiba G, Kocsy G, Hasanuzzaman M, Nahar K, Anee T.I., Fujita M., experimentally confirmed the role of GSH as AOs (Szalai et al., 2009; Hasanuzzaman et al., 2017, 2019). According to Gautam V., Kaur R., Kohli S.K., Verma V., Kaur P., Singh R., Saini P., Arora S., Thukral A.K., Karpets Yu, Bhardwaj R. the first PO that occurs in a plant cell as a by-product of photosynthesis is singlet oxygen, which is converted to superoxide anion radical ($\bullet O_2^-$) (Gautam et al., 2017). The target of $\bullet O_2^-$ is cell membranes, which as a result of FRPO, form malondialdehyde (MDA) and other TBA-active products (Morales and Munné-Bosch, 2019). A marker of membrane damage is the change in cytochrome oxidase activity, the significance of which is described by Wikström (Wikström et al., 2018). The balance between the formation and POs, and protective effect of AOs is PAS, which at the molecular level responds to the impact of any factors on the body's homeostasis (Dat et al., 2000; Dickinson, 2003; Gill and Tuteja, 2010; Huang & Guo, 2005).

The role of antioxidant in seed quality is described in Mahalingam Govindaraj′s work (Govindaraj et al., 2017), antioxidant activity and phenolic content of selected fruit seeds is described by Yean-Yean Soong and Philip J Barlow (Soong & Barlow, 2004). Identification and quantification of polyphenols in hull, bran and endosperm of common buckwheat is shown in Zhang′s article (Zhang et al., 2017). Pang and his

colleagues investigated the bound phenolic compounds and antioxidant properties of whole grain and bran of white, red and black rice (Pang et al., 2018). Comparison of phenolic profiles and antioxidant properties of European Fagopyrum esculentum cultivars is shown in Kiprovski's article (Kiprovski et al., 2015). There is no systematic material describing the effect of storage duration on the content of antioxidants in the seeds of agricultural plants, which increases the relevance of our research.

Methodology

Seed tissues of the following plants were the object of experimental studies: *Glycine max L., Helianthus annuus L., Fagopyrum esculentum L., Linum usitatissimum L., Sinapis alba L., Chenopodium quinoa L., Panicum miliaceum L., Oryza sativa L., Avena sativa L., Zea mays L., Hordeum vulgare L, Triticum durum Desf*. The choice of plant species is due to the popularity of their use in the daily diet and the recommendation of nutritionists regarding a healthy diet.

To create the research scheme, we were guided by the fact that the first and main pro-oxidant, which is formed in the cells of all living beings in response to stressors, is the superoxide anion radical. A marker of the strengthening of the pro-oxidant link is its effect on lipid membranes with their subsequent peroxidation and the formation of TBA-active products. The main enzymatic antioxidants of cells are superoxide dismutase and catalase, and low-molecular ones - ascorbic acid and glutathione. The effectiveness of maintaining the pro-oxidant-antioxidant balance is assessed by the activity of cytochrome oxidase. So, by experimentally investigating the changes in the above indicators, it is possible to draw a conclusion about the state of the pro-oxidant-antioxidant system, and in our case to draw conclusions about the degree of benefit of the selected food products.

To quantify the change in the value of PAS indicators, we used generally accepted classical methods described in detail in our previous works (Bobrova et al., 2020, 2021, 2022). Thus, the baseline level of $\bullet O_2^-$ generation was determined using the spectrophotometric nitroblue tetrazolium recovery test (NBT test), the advantage of which is high accuracy and the possibility of determining both the basic level of superoxide generation and its sources, namely mitochondrial, microsomal or cytoplasmic. The chosen method for determining TBA-active products includes pre-incubation of the homogenate in a pro-oxidant ferrum-ascorbinate buffer with longer photometry, which allows not only to determine the content of malondialdehyde, but also to draw a conclusion about the general degree of free radical damage to membrane lipids. To assess the change in SOD activity, the percentage of inhibition of the oxidation of $\bullet O_2^-$ adrenaline into adrenochrome was determined, and catalase was determined by titration with potassium permanganate solution, which are classical generally accepted biochemical techniques. The content of AA was determined according to Tillmans titrimetry, and the concentration of GSH was determined by the Elman method, which do not require lengthy sample preparation, combine accuracy and ease of execution, allow selective determination of experimental components with maximum preservation of their nativeness. Cytochrome oxidase activity was determined spectrophotometrically. The peculiarity of the technique is extremely strict observance of the conditions for the preservation of cytochrome to prevent its oxidation. Biochemical parameters were measured monthly for 1 year. All experiments were carried out under standard conditions (air temperature 20 degrees Celsius and absolute pressure 760 mmHg, air humidity 50%). Each control and experimental group included 10 samples when determining each indicated indicator.

Results and Discussion

The results of the study were statistically calculated according to generally accepted methods, the reliability was confirmed at $p < 0.05$. The repetition of samples for each indicator given in the table is 10. The laboratory analysis of all mentioned indicators was carried out in strict accordance with the order and conditions of conducting the experiment specified in the methods. All experiments were conducted under standard conditions (air temperature 20 degrees Celsius and absolute pressure 760 mmHg, air humidity 50%). The seeds were stored under standard conditions and without access to light. This minimizes potential sources of error and enables the generalization of the results.

For ease of calculation and better clarity of the digital data, we present the baseline level of POs and AOs in the tissues **(Tables 1 and 2).** In our previous work, we investigated the effect of germination initiation on the pro-oxidant-antioxidant balance and determined the baseline values of PAS state indicators that are species-specific. Using these results, we set up two experimental lines in parallel: the first involved the

initiation of the seed germination process, which is reflected in our 2022 publication (Bobrova et al., 2022). The second direction, the results of which this article is devoted to, included a change in the values of all starting indicators depending on the duration of seed storage, which we fixed every month during the year. The common point of intersection of these two directions of scientific research is the starting level of indicators of the state of PAS, so we consider it appropriate to present in this publication the results of laboratory studies of the basic level of PAS established by us earlier. This need is also justified by the fact that we calculated the results of monthly changes in the values of PAS status indicators as a percentage of the base level, which is the most convenient way to summarize the results on one graph for indicators with different measurement units.

Table 1.
Results of identification of prooxidant activity and the level of FRPO in the inactive seed tissues

Experimental plants	Indicators of prooxidant activity		The level of FRPO damage
	NBT test (base level), nmol•O_2^-/grams·second	ΔTBA_{ap}, %	Cytochrome oxidase activity, OD
Glycine max L.	0,072 ±0,011	66,15 ± 5,01	0,314 ±0,019
Helianthus annuus L.	1,134 ± 0,042	42,23 ± 1,06	0,204±0,003
Fagopyrum esculentum L.	0,287 ± 0,019	99,22 ± 4,11	0,183±0,005
Linum usitatissimum L.	1,006 ± 0,011	29,88 ± 1,44	0,262±0,009
Sinapis alba L.	0,778 ± 0,021	35,18 ± 1,22	0,240±0,004
Chenopodium quinoa L.	0,122 ± 0,014	85,14 ± 3,67	0,436 ±0,011
Panicum miliaceum L.	1,086±0,011	136,49 ± 6,22	0,118±0,006
Oryza sativa L.	0,437±0,010	21,63 ± 1,10	0,398 ±0,006
Avena sativa L.	0,036±0,004	11,27 ± 2,01	0,418 ±0,009
Zea mays L.	1,273±0,015	111,83 ± 5,19	0,159±0,008
Hordeum vulgare L.	0,091±0,009	128,45 ± 18,35	0,276±0,005
Triticum durum Desf.	0,090 ±0,009	27,86 ± 4,11	0,346 ±0,001

Source: compiled by the authors based on a previous publication (Bobrova, et al., 2022).

Table 2.
Results of identification of antioxidant activity in the inactive seed tissues

Experimental plants	Enzyme antioxidants		Low molecular weight antioxidants	
	Catalase activity, $\frac{micromol}{kg*min}$	SOD Activity, OD	AA concentration, $\frac{mmoL}{kg}$	GSH concentration, $\frac{mmol}{kg}$
Glycine max L.	0,48 ± 0,02	0,53 ± 0,02	0,293 ± 0,03	59,32 ± 0,95
Helianthus annuus L.	0,19 ± 0,01	0,28 ± 0,01	0,096 ± 0,01	39,11 ± 0,72
Fagopyrum esculentum L.	0,31 ± 0,02	0,28 ± 0,02	0,141 ± 0,02	43,22 ± 0,96
Linum usitatissimum L.	0,11 ± 0,01	0,30 ± 0,01	0,135 ± 0,02	46,79 ± 0,48
Sinapis alba L.	0,25 ± 0,01	0,36 ± 0,03	0,110 ± 0,01	41,01 ± 0,63
Chenopodium quinoa L.	0,36 ± 0,01	0,44 ± 0,02	0,120 ± 0,02	51,67 ± 0,11
Avena sativa L.	0,39 ± 0,03	0,46 ± 0,02	0,111 ± 0,03	54,19 ± 0,34
Oryza sativa L.	0,31 ± 0,01	0,42 ± 0,01	0,092 ± 0,01	45,18 ± 0,78
Hordeum vulgare L.	0,23 ± 0,02	0,29 ± 0,01	0,076±0,01	48,05 ± 0,10
Triticum durum Desf.	0,09 ± 0,02	0,22 ± 0,01	0,057 ± 0,01	40,79 ± 0,25
Zea mays L.	0,09 ± 0,01	0,19 ± 0,01	0,085 ± 0,02	37,16 ± 0,99
Panicum miliaceum L.	0,07 ± 0,01	0,16 ± 0,01	0,037 ± 0,01	43,14 ± 0,67

Source: compiled by the authors based on a previous publication (Bobrova, et al., 2022).

Analysing the results obtained, it can be stated that soybean seeds have the lowest baseline level of PO activity, the highest content of both enzymatic and low-molecular weight AOs, therefore the lowest percentage of increase in •O_2^- and the lowest percentage of decrease in the content of SOD and catalase **(Fig. 1)**. The relatively stable level of GSH is noteworthy.

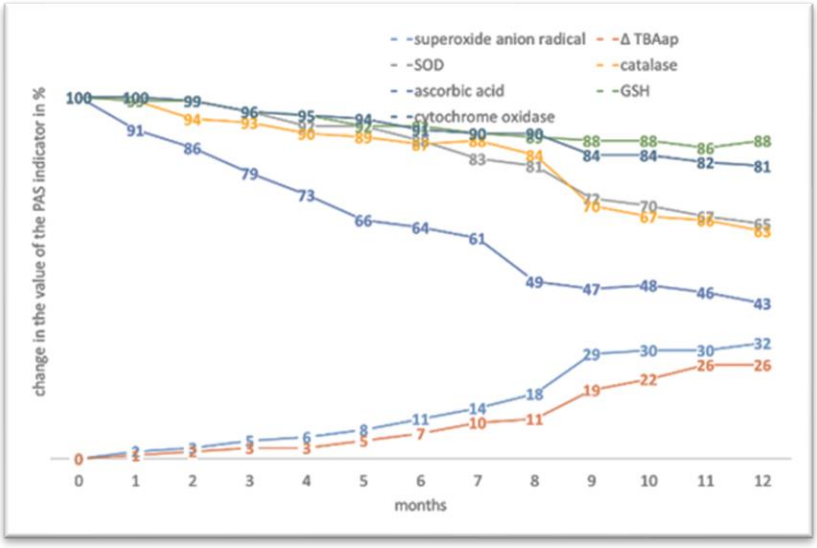

Figure 1. The effect of storage time on the change in the value of the PAS indicators in the tissues of *Glycine max L* seeds.

A similar pattern was found in the tissues of quinoa seeds **(Fig. 2):**

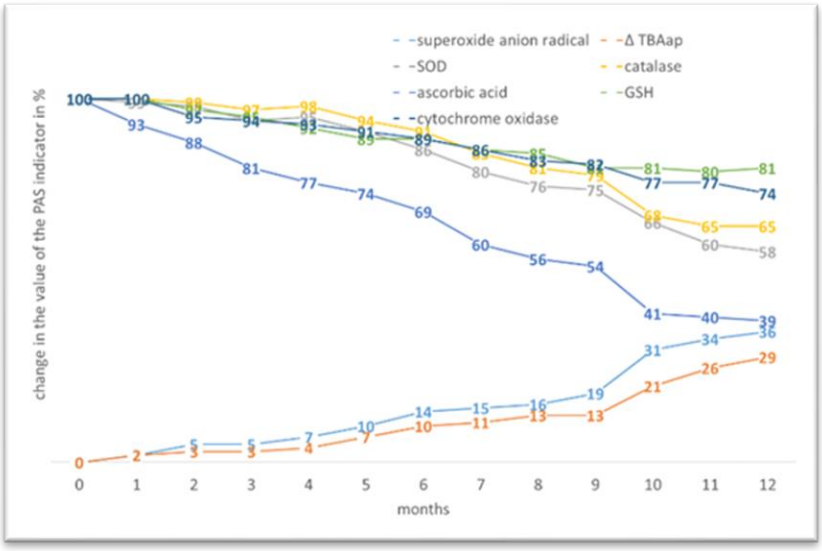

Figure 2. The effect of storage time on the change in the value of the PAS indicators in *Chenopodium quinoa L*. seed tissues.

A characteristic feature of buckwheat was a relatively stable level of AA, the smallest increase in ΔTBA_{ap} and the smallest decrease in cytochrome oxidase, a possible explanation for this is the high content of essential amino acids, potassium, magnesium and iron, which is part of cytochrome **(Fig. 3).**

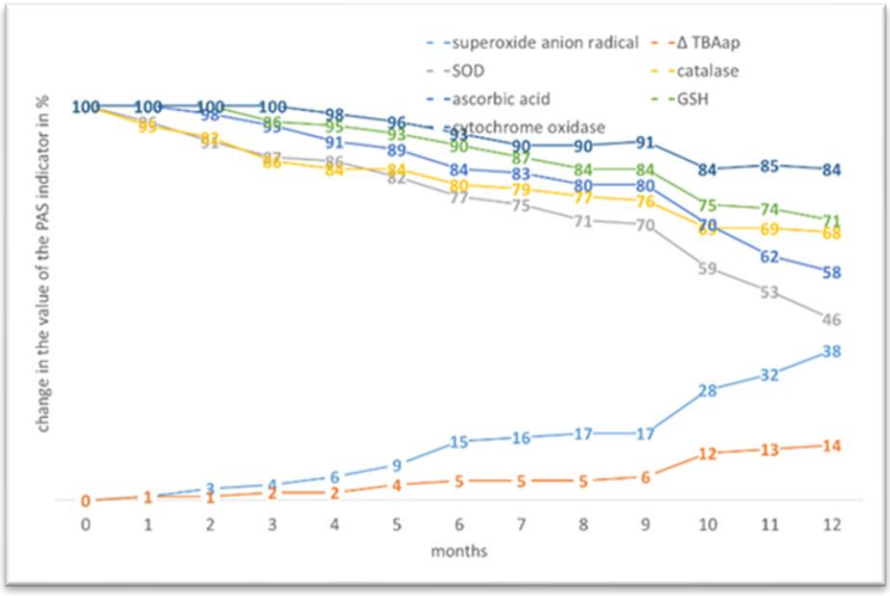

Figure 3. The effect of storage time on the change in the value of the PAS indicators in the tissues of *Fagopyrum esculentum L*. seeds.

A characteristic feature of flax was one of the lowest increases in ΔTBA_{ap} with a fairly high increase in $\bullet O_2^-$, which may be explained by the presence of polyunsaturated fatty acids (PUFA) **(Fig. 4).**

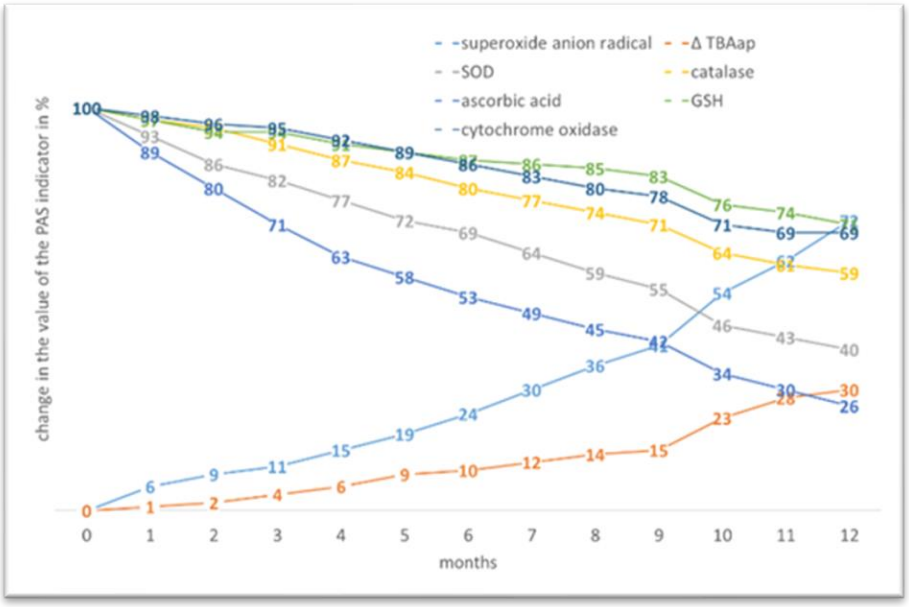

Figure 4. The effect of storage time on the change in the value of the PAS indicators in *Linum usitatissimum L*. seed tissues.

Among dicotyledons, sunflower has the highest percentage of increase in PO activity with increasing storage time, which is explained by a rather high initial level of $\bullet O_2^-$ generation **(Fig. 5).** The decrease in the content of enzymatic and low molecular weight AOs is also the largest, since their initial level was the lowest among all the experimental samples of dicotyledonous seed tissues.

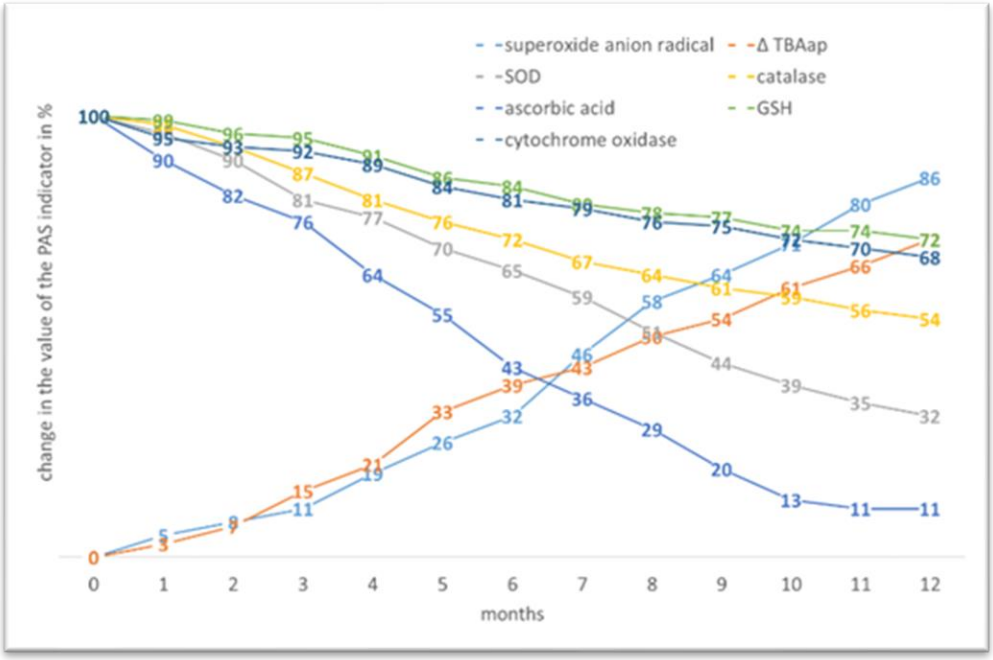

Figure 5. The effect of storage time on the change in the value of the PAS indicators in the tissues of *Helianthus annuus L*. seeds.

In the tissues of buckwheat, mustard **(Fig. 6)** and flax, we observe intermediate values of the increase in PO activity and a decrease in the content of AOs with an increase in storage time.

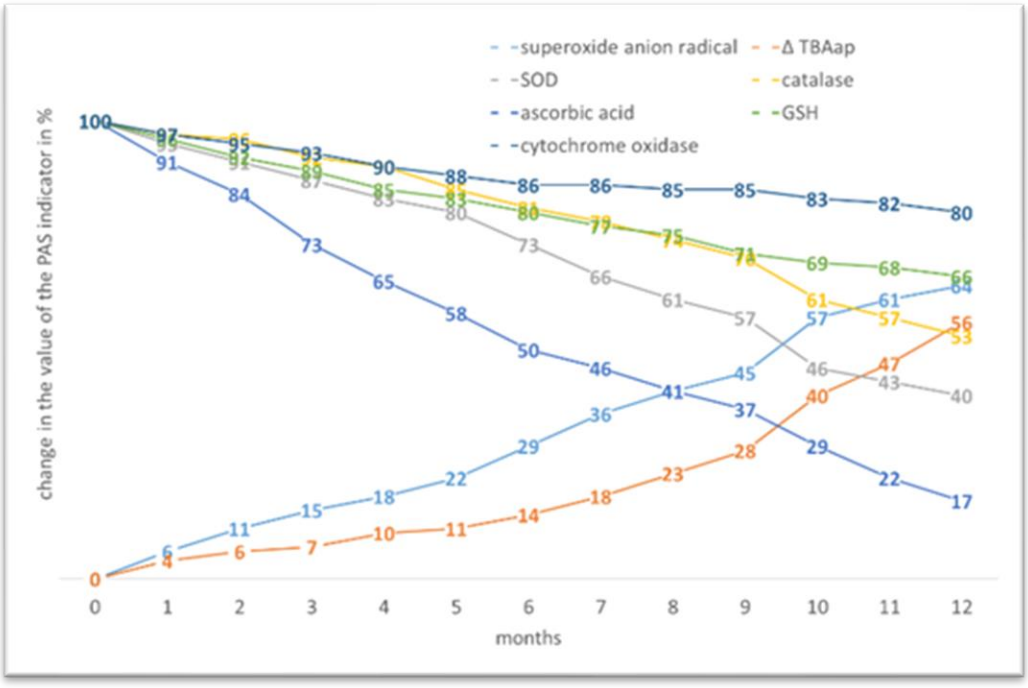

Figure 6. The effect of storage time on the change in the value of the PAS indicators in *Sinapis alba L*. seed tissues.

Thus, we obtain a tendency of dependence of the percentage of increase in the level of FRPO and decrease in AO protection with an increase in the storage time of tissues on the value of the initial level of PAS indicators.

Among monocotyledons, oats have the highest rates of preservation of AO properties with increasing seed storage time **(Fig. 7)**. It also has the lowest increase of $\bullet O_2^-$ and ΔTBA_{ap}.

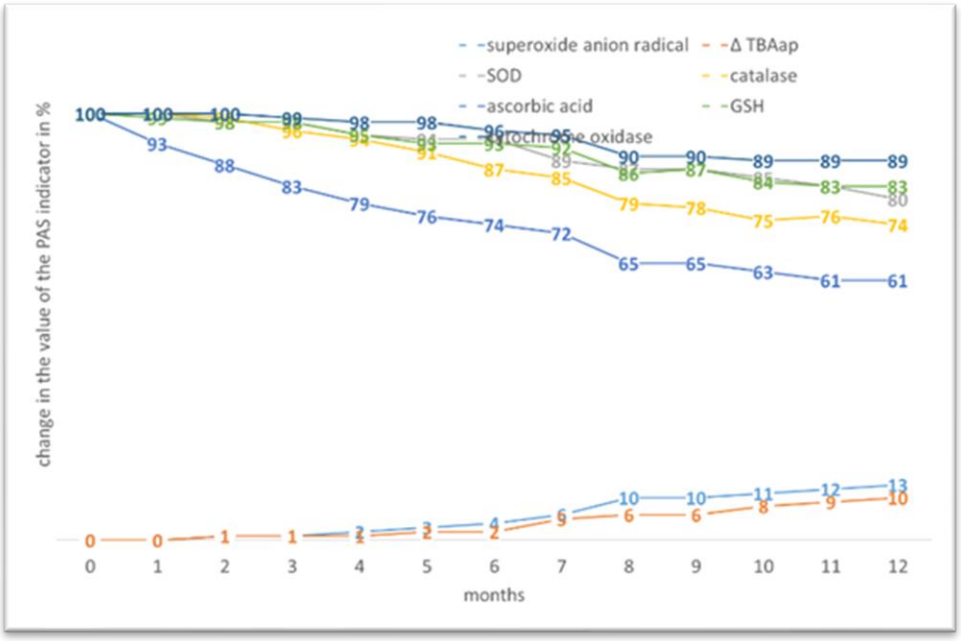

Figure 7. The effect of storage time on the change in the value of the PAS indicators in *Avena sativa L.* seed tissues.

The worst results are observed for maize. However, it is interesting that with the greatest increase in $\bullet O_2^-$ and ΔTBA_{ap}, the greatest decrease in AO, the cytochrome oxidase activity is quite high, possibly due to the involvement of β-carotenes in stabilisation **(Fig. 8).**

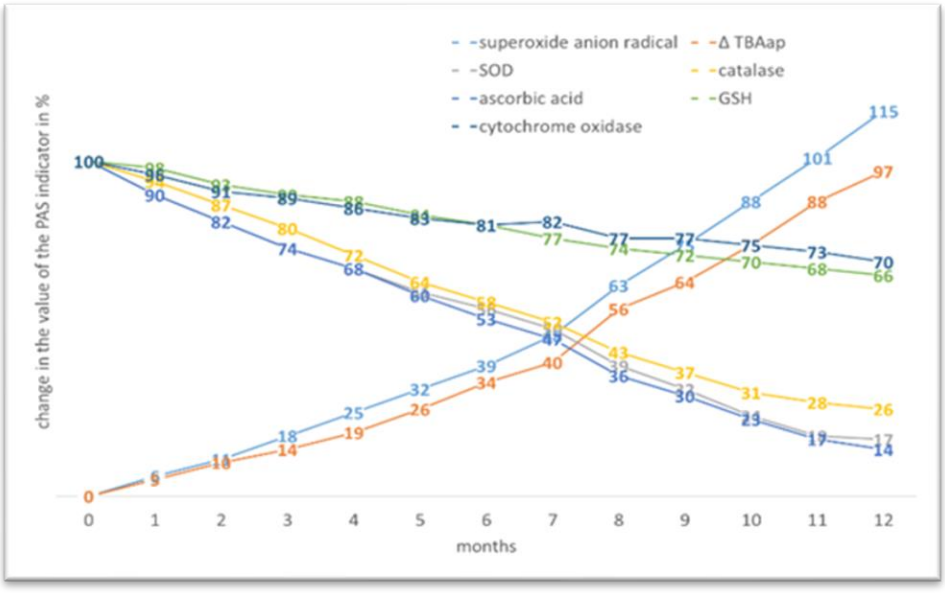

Figure 8. The effect of storage time on the change in the value of the PAS indicators in *Zea mays L.* seed tissues.

Millet has similar changes in the values of indicators to maize. However, the decline in non-enzymatic AOs is not as intense, however, taking into account their initial low level. The stability of GSH stands out against this background. Millet is also characterised by the largest decrease in cytochrome oxidase activity **(Fig. 9).**

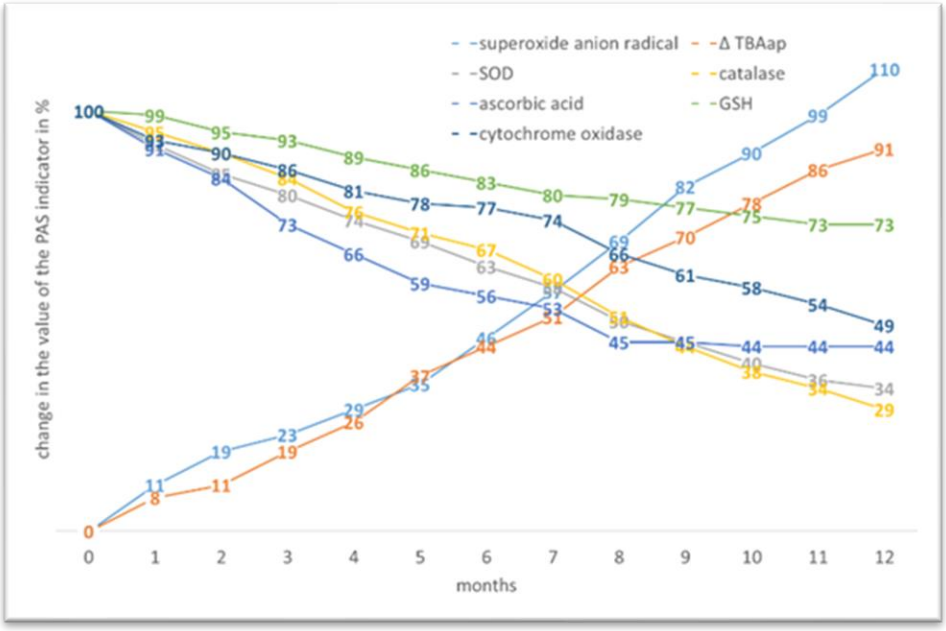

Figure 9. The effect of storage time on the change in the value of the PAS indicators in the tissues of *Panicum miliaceum L*. seeds.

A characteristic feature of rice is a significant decrease in the intensity of the decline in the level of AOs after 6-7 months of storage. Stable decrease of GSH and intermediate indicators of PO activity between the previously described monocots **(Fig. 10).**

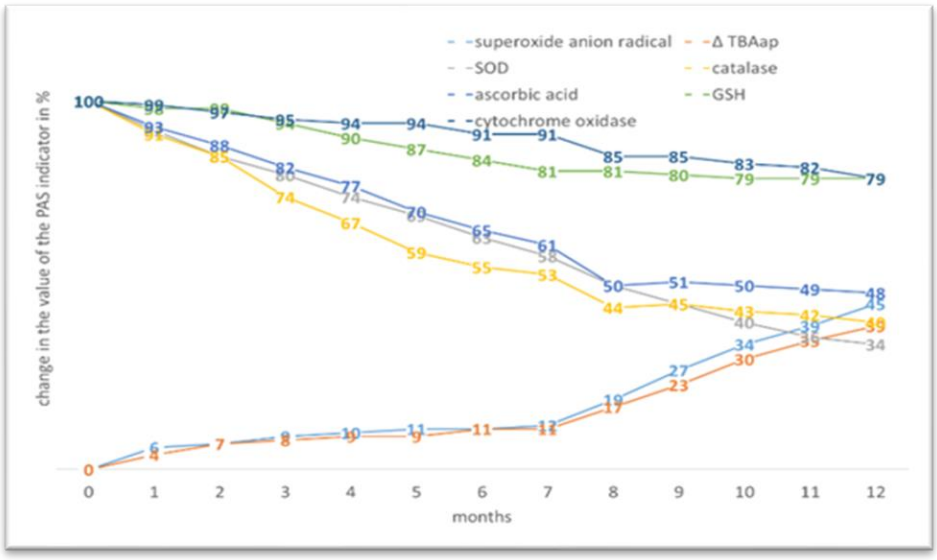

Figure 10. The effect of storage period on the change in the value of the PAS indicators in *Oryza sativa L*. seed tissues.

Indicators of wheat and barley show similarities in the change of PAS values **(Fig. 11, Fig. 12, respectively).**

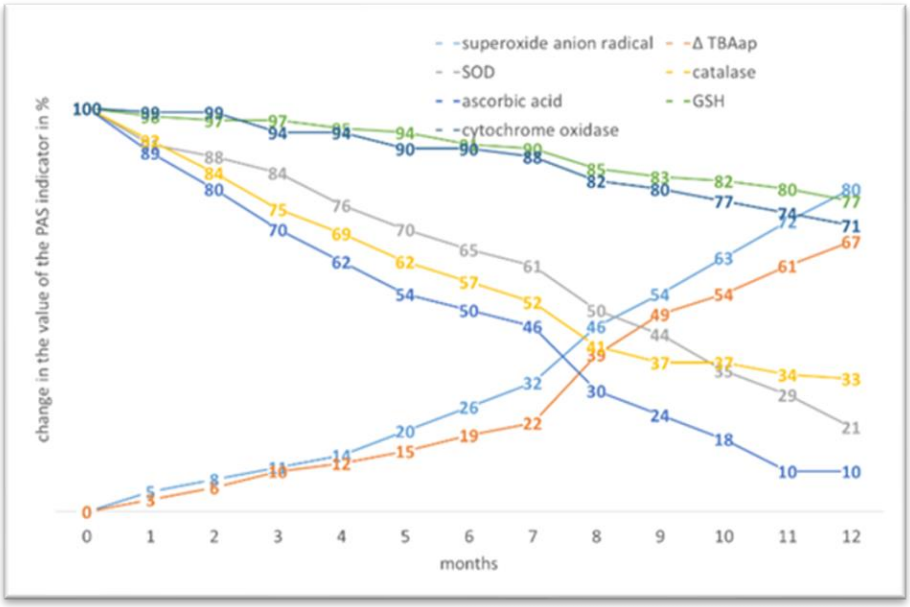

Figure 11. The effect of storage time on the change in the value of the PAS indicators in *Triticum durum Desf*.

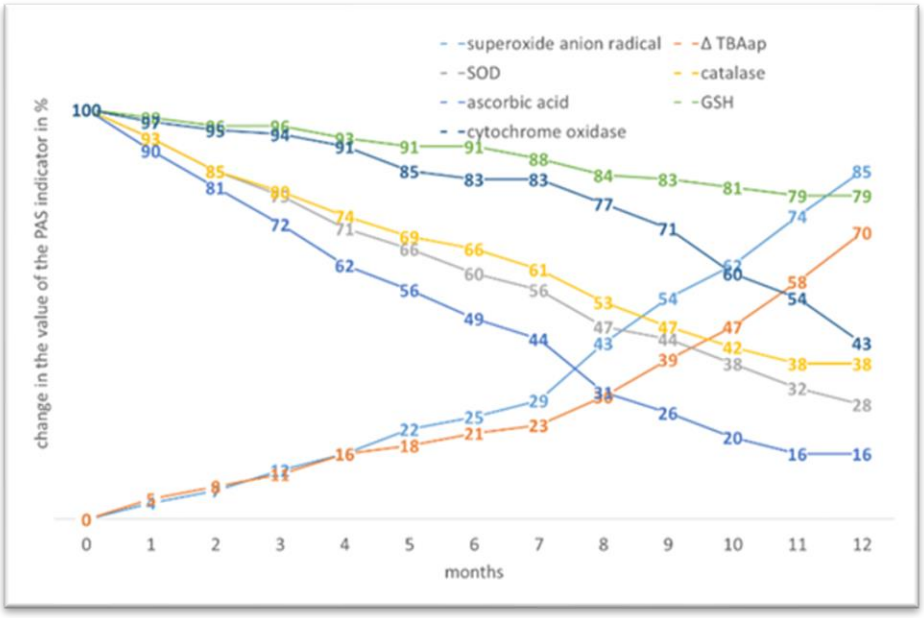

Figure 12. The effect of storage time on the change in the value of the PAS indicators in *Hordeum vulgare L*. seed tissues.

Summing up all the above, we have identified a pattern according to which an uprise in the growth of PO activity and a corresponding decrease in AO activity, which occurs at 9-10 months of storage, is characteristic of the seed tissues of all dicotyledonous experimental samples, while for monocotyledons this uprise occurs at 6-7 months, which indicates an increased sensitivity of seeds to changes in environmental factors and the effects of stress factors. This must be taken into account to ensure the optimal time for planting and caring for seeds.

GSH does not follow this pattern, it has a stable decrease in content, but in no case does it decrease below 60 %, which may indicate its leading role.

It was observed that the overall increase in PO activity with increasing storage time is higher in monocots, and the decrease in AO content is lower in dicots. This may be explained by the quantitative and qualitative

composition of cellular inclusions, which perform not only reserve, trophic, but also protective functions. For example, PUFAs in flax, mustard and sunflower tissues are free radical protectors, and the increased content of protein inclusions in soybean and quinoa tissues is a source of amino acids in the synthesis of enzymatic AOs. The valuable biochemical composition of buckwheat, with its high content of arginine, lysine, cystine, histidine, phosphoric acid, potassium, magnesium and iron, promotes the synthesis of both enzymatic and low-molecular weight AOs.

Conclusion

1) The activity of enzymatic antioxidants decreases with increasing storage time. The average value for catalase is 50.15% (60.3% for dicotyledons, 40% for monocots), for SOD – 41.25% (46.8% for dicotyledons, 35.7% for monocots) of the initial level. According to the preservation of catalase activity with the increase of seed storage time, the experimental plants form the following series: *Avena sativa L., Fagopyrum esculentum L., Chenopodium quinoa L., Glycine max L., Linum usitatissimum L., Helianthus annuus L., Sinapis alba L., Oryza sativa L., Hordeum vulgare L., Triticum durum Desf. Panicum miliaceum L., Zea mays L*. The sequence of plants by preservation of SOD activity is as follows: *Avena sativa L., Glycine max L., Chenopodium quinoa L., Fagopyrum esculentum L., Sinapis alba L., Linum usitatissimum L., Oryza sativa L., Panicum miliaceum L., Helianthus annuus L., Hordeum vulgare L., Triticum durum Desf. Zea mays L*.
2) The concentration of low-molecular-weight antioxidants decreases with increasing storage time. The average value for AA is 32.15% (32.3% for dicotyledons, 32.2% for monocots), for GSH - 75.6% (75% for dicotyledons, 76.2% for monocots) of the initial level. According to the preservation of ascorbic acid concentration with the increase of seed storage time, the experimental plants form the following series: *Avena sativa L., Fagopyrum esculentum L., Oryza sativa L., Panicum miliaceum L., Glycine max L., Chenopodium quinoa L., Linum usitatissimum L., Sinapis alba L., Hordeum vulgare L., Zea mays L., Helianthus annuus L., Triticum durum Desf*. The sequence of plants by preservation of GSH content is as follows: *Glycine max L., Avena sativa L., Chenopodium quinoa L., Oryza sativa L., Hordeum vulgare L., Triticum durum Desf., Panicum miliaceum L., Linum usitatissimum L., Helianthus annuus L., Fagopyrum esculentum L., Sinapis alba L., Zea mays L*.
3) The increase in the content of superoxide radical in the seed tissues of the experimental plants with an increase in the storage period to 12 months is 64.7% on average (54.7% for dicotyledons, 74.7% for monocots). According to the increase of superoxide concentration with the increase of seed storage time, the experimental plants form the following row: *Avena sativa L., Glycine max L., Chenopodium quinoa L., Fagopyrum esculentum L., Oryza sativa L., Sinapis alba L., Linum usitatissimum L., Triticum durum Desf. Hordeum vulgare L., Helianthus annuus L., Panicum miliaceum L., Zea mays L*.
4) The concentration of TBA-active tropoids in the seed tissues of the experimental plants increased by an average of 50.15% over 12 months of storage (37.8% for dicotyledons, 62.3% for monocots). According to the increase in the content of TBA-active tropoids with the increase in the storage time of seeds, the experimental plants form the following series: *Avena sativa L., Fagopyrum esculentum L., Glycine max L., Chenopodium quinoa L., Linum usitatissimum L., Oryza sativa L., Sinapis alba L., Triticum durum Desf. Hordeum vulgare L., Helianthus annuus L., Panicum miliaceum L., Zea mays L*.
5) Cytochrome oxidase activity decreased by 71.4% on average during the experiment (76% for dicotyledons, 66.8% for monocots). The sequence of plants according to the preservation of cytochrome oxidase activity in seed tissues during one-year storage is as follows: *Avena sativa L., Fagopyrum esculentum L., Glycine max L., Sinapis alba L., Oryza sativa L., Chenopodium quinoa L., Triticum durum Desf., Zea mays L., Linum usitatissimum L., Helianthus annuus L., Panicum miliaceum L., Hordeum vulgare L*.
6) The percentage of increase in the level of RPE and decrease in the FRPO of protection with an increase in the storage time of tissues depends on the value of the starting level of the PAS indicators.
7) The overall increase in PO activity with increasing storage period is higher in monocots, and the decrease in AO content is lower in dicots.
8) The seed tissues of all dicotyledonous experimental samples are characterised by an uprise in the growth of PO activity and a corresponding decrease in AO activity, which occurs at 9-10 months of storage, while for monocotyledons this uprise occurs at 6-7 months, indicating an increased sensitivity of seeds to changes in environmental factors and the effects of stress factors, which should be taken into account to ensure the optimal time for planting and caring for seeds.

The prospect of further scientific research is the study of changes in the content of antioxidants, free radicals and their transformation products in the edible parts of fruits and vegetables, as well as the search for ways

to preserve their antioxidant activity. It is of great practical importance in nutrition, food hygiene and increased relevance among supporters of a healthy lifestyle.

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