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Study of Wheat (*Triticum aestivum* L.) Seed Deterioration Pattern Using a Systems Approach

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ABSTRAK

Benih gandum, sebagai salah satu jenis benih ortodoks, secara alami mengalami penurunan mutu selama penyimpanan jangka panjang. Proses kemunduran ini bersifat kompleks dan melibatkan berbagai faktor sepanjang siklus hidup benih. Namun demikian, kajian mengenai deteriorasi benih umumnya masih didasarkan pada pendekatan statis. Oleh karena itu, peralihan dari indikator statis menuju indikator dinamis, yang mampu menggambarkan perubahan kondisi sistem biologis benih dari waktu ke waktu, menjadi hal yang menarik untuk dikaji. Penelitian ini bertujuan untuk mengestimasi vigor dan daya simpan benih gandum berdasarkan pendekatan sistem. Penelitian dilaksanakan menggunakan pendekatan sistem, dengan tahapan meliputi studi literatur dan pengumpulan data dari beberapa jurnal ilmiah, penyusunan diagram alir, pengembangan model, simulasi, serta validasi. Hasil penelitian menunjukkan bahwa estimasi deteriorasi benih gandum dapat diprediksi melalui pendekatan sistem. Estimasi deteriorasi benih gandum merupakan suatu sistem yang melibatkan banyak variabel yang saling berkaitan dan berlangsung secara simultan. Model estimasi deteriorasi benih gandum dapat dihitung menggunakan persamaan berikut: ROS(t) = ROS(t - dt) + (-H_2O_2) x dt; H_2O_2 = ROS x Changes index of H_2O_2; MDA = 4.62271 + (18.4012 - 4.62271) x exp (-22.2767 x $H_2O_2{}^{1.70613}$); FFA = 123.336 x exp (-10.1865 x H_2O_2); daya kecambah = 2.30234 + (109.524 - 2.30234) / (1 + exp (11.4657 x ln ('MDA' / 9.39342))). Selama penyimpanan, enzim antioksidan yang berperan dalam menguraikan spesies oksigen reaktif (reactive oxygen species/ROS) menjadi tidak aktif. Akumulasi ROS menyebabkan kerusakan membran, yang selanjutnya menurunkan vigor benih, ditandai dengan berkurangnya daya kecambah.

Kata kunci: Daya kecambah, mutu, penyimpanan, viabilitas, vigor.

ABSTRACT

Wheat seeds, one of the orthodox seed types, naturally experience a decline in quality during long-term storage. This deterioration is a complex process that involves various factors throughout the seed's lifecycle. However, seed deterioration studies are based on static approaches. Therefore, moving from static to dynamic indicators, which describe changes in the state of seed biological systems over time, would be exciting. The study aimed to estimate the vigor and storability of wheat seeds based on a systems approach. The research was carried out using a systems approach, while the stages of the research were as follows: literature study and data collection from several scientific journals, preparation of flowcharts, models, simulations, and validation. The results showed that the estimation of wheat seed deterioration could be predicted through a systems approach. The estimation of wheat seed deterioration is a system that involves many variables that are interrelated and occur simultaneously. The following equations can estimate the wheat seed deterioration model: ROS(t) = ROS(t - dt) + (-H_2O_2) x dt; H_2O_2 = ROS x Changes index of H_2O_2; MDA = 4.62271 + (18.4012 - 4.62271) x exp (-22.2767 x $H_2O_2{}^{1.70613}$); FFA = 123.336 x exp (-10.1865 x H_2O_2); germination = 2.30234 + (109.524 - 2.30234) / (1 + exp (11.4657 x ln ('MDA' / 9.39342))). During storage, antioxidant enzymes that degrade reactive oxygen species (ROS) become inactive. The accumulation of ROS leads to membrane damage, resulting in decreased vigor, which is characterized by reduced germination rates.

Keywords: Germination, quality, storage, viability, vigor.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the primary cereal grains consumed worldwide (Mansouri et al. 2015; Elasraag and Alarcón 2017; Li et al. 2022), including in Asia and Africa (Reynolds 2021). Wheat seed is an orthodox seed that can be stored for a long time under controlled storage (Zhang et al. 2014; Solberg et al. 2020). However, like other organisms, the physicochemical properties of wheat seeds naturally change due to deterioration processes, which affect the seeds' viability and quality (Pinheiro et al., 2020; Varzakas, 2017; Krupnik et al., 2022). During storage, postharvest wheat seeds continue to utilize stored nutrients to generate energy and sustain their metabolism (Matthews et al. 2012). This metabolic activity can lead to quality changes within the internal structure of the seeds, including loosening of tissue structure, reduced nutrient levels, and decreased enzymatic activity. These changes can result in physiological damage to the wheat embryos and a decline in seed viability (Walters 1998; Marshall and Lewis 2009; Rajarammanna et al. 2010; Spano et al. 2011). As a result, the deterioration of wheat seed during storage has received increasing attention in recent years.

Seed vigor is defined as the seed's ability to resist the effects of senescence (Ventura et al. 2012). Consequently, seed vigor and seed deterioration are interconnected phenomena. The highest physiological quality of seeds is typically achieved at physiological maturity (Shelar et al. 2008). After reaching maturity, a seed's metabolic activity initiates continuous biochemical changes, primarily involving catabolic processes that lead to seed deterioration (Ma et al. 2017). This deterioration, manifested as a decline in physiological quality, ultimately reduces germination and seed vigor (Fu et al. 2015). Seed deterioration is an inevitable and irreversible process, meaning the catabolic changes (such as denaturation) in deteriorated seeds cannot be undone. Estimating seed vigor is crucial for predicting how long seeds can be effectively stored, as vigor is closely linked to the complex process of seed deterioration. Deterioration occurs during both open and controlled storage conditions.

The causes of seed deterioration and decreased shelf life are not completely understood, as senescence is a complex biological property involving various molecular, tissue, biochemical, physiological, and metabolic processes (Fu et al. 2015). However, several studied processes have established cause-and-effect relationships related to seed damage. These include reduced mitochondrial activity (Xin et al. 2014), Amadori and Maillard reactions (Murthy et al. 2000; Murthy et al. 2003; Nisarga et al. 2017), and the inactivation of hydrolytic enzymes and antioxidants (Ali et al., 2017; Sharma et al., 2013). According to Justice and Bass (1979), internal factors affecting seed deterioration include initial seed viability, moisture content, and genetic factors such as variety, seed size, permeability, and chemical composition. In contrast, external factors include the physical environment (temperature, relative humidity of air, atmosphere) and biotic (viruses, fungi, bacteria, and pests).

Seeds are living organisms, and like all living beings, they inherently undergo changes over time in aspects such as growth rate, vigor, and germination. In addition, the seed deterioration process is complex (Copeland and McDonald 2001). In general, the estimation of the seed deterioration process is not based on a systems approach, so it cannot fully explain the process (Komarov et al. 2021). The system is a mechanism where various components interact to form a function, and its simplification is called a model (Komarov et al. 2021; Handoko 2005; Wei et al. 2019). Seed deterioration during storage is a dynamic system, so it is a model that fits the concept of seed deterioration. Therefore, moving from static to dynamic indicators, which describe changes in the state of biological systems (seeds) over time, would be exciting. Indicators of seed germination are used to support the transition from a static to a dynamic approach.

The dynamic model of wheat seed vigor is expected to be used to obtain information effectively and efficiently. Therefore, wheat seed vigor and shelf life information can be obtained quickly and accurately to determine seed viability before planting in the field. This model is built based on the process approach that occurs during storage to provide accurate results. Therefore, the study aimed to estimate the vigor and storability of wheat seeds based on a systems approach. The presented model reveals the possibility of developing methods for assessing the seed quality of other crops.

MATERIALS AND METHODS

The process of seed deterioration, including that of wheat seeds, is complex. Seed deterioration during storage operates as a dynamic system, which aligns with the concept of seed damage (Komarov et al. 2021). A system is defined as a mechanism where various components interact to form a specific function, and a simplified representation of this is called a model (Handoko 2005; Wei et al. 2019; Komarov et al. 2021). Consequently, this research utilized a systems approach, which involved several stages (Handoko 2005): literature study and data collection from several scientific journals, creating a flowchart, models, simulations, and model validation (Figure 1).

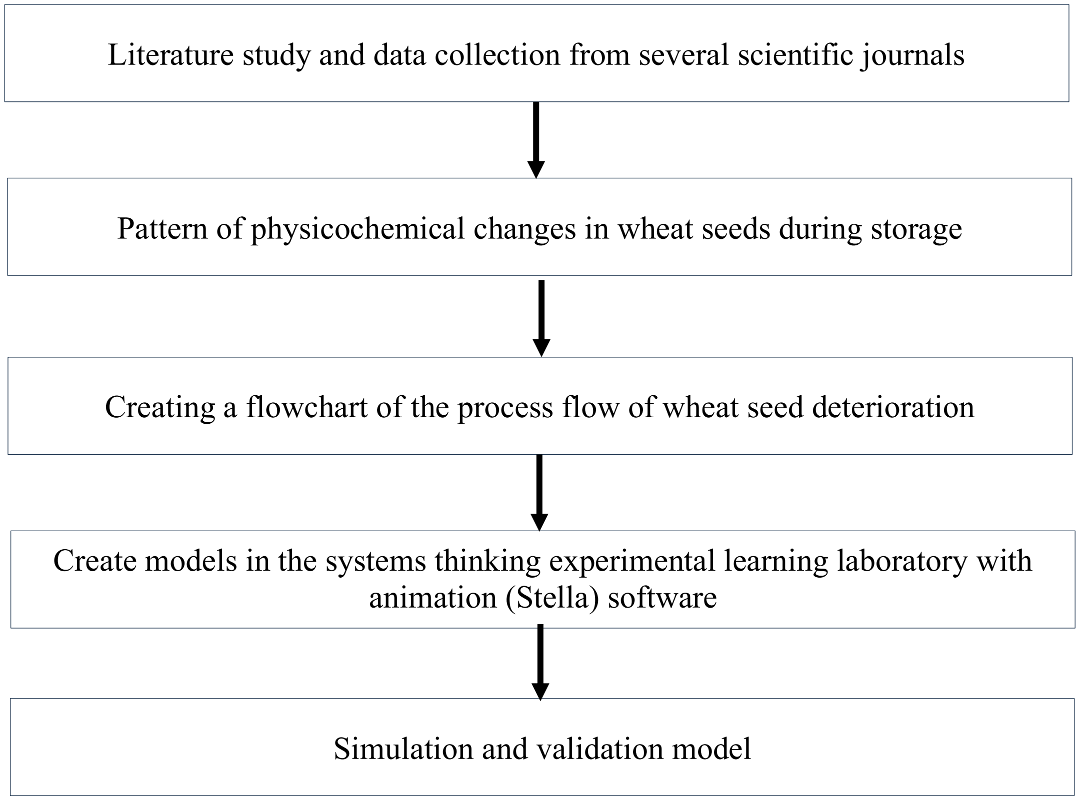

Figure 1. The stages for estimating wheat seed deterioration by a systems approach.

1. Literature study and data collection from several scientific journals.

A literature study was conducted to develop the basic concepts of the wheat seed deterioration process, the mathematical relationships between variables in the wheat seed deterioration process, the constants and variables needed to construct the mathematical relationships between variables in the wheat seed deterioration process, data for model input in simulations, and data for model verification. A literature study was conducted to obtain information regarding the quantitative relationship between components in the system and the relationship between external variables (storage conditions) and internal variables (seeds) during wheat seed storage. The data on the physicochemical changes of wheat seed used such as moisture, enzyme activity (dehydrogenase, catalase and peroxidase), reactive oxygen species (ROS), malondialdehyde (MDA), H_2O_2, free fatty acid (FFA), and germination, where variables used are interrelated processes and appear simultaneously.

2. Pattern of physicochemical changes in wheat seeds during storage.

The physicochemical changes in wheat seeds, specifically moisture, enzyme activity, reactive oxygen species (ROS), malondialdehyde (MDA), hydrogen peroxide (H_2O_2), free fatty acids (FFA), and germination, were analyzed based on data obtained from literature studies. A statistical analysis employing regression techniques was conducted to investigate these changes during the storage of wheat seeds. The analysis was performed using Minitab 16 software. The insights gained from this study will contribute to developing a model for predicting the deterioration of wheat seeds.

3. Creating a flowchart of the process of wheat seed deterioration.

The process of mass flow of water from the storage chamber into the seeds is described in terms of flow with the various external and internal variables involved, which are initiated by the absorption of moisture from the storage chamber through the seed coat. Seed imbibition increases seed moisture content and affects enzyme activity. Enzyme activity is used for the degradation of carbohydrates and amino acids through respiration, which causes a reduction in seed growth energy and damage to cell membranes, ultimately reducing seed vigor.

Estimating the deterioration pattern of wheat seed through a systems approach is carried out by estimating the physiochemical changes of wheat seed as a whole system where variables used are interrelated processes and appear simultaneously. The process flow of wheat seed deterioration is presented in Figure 2.

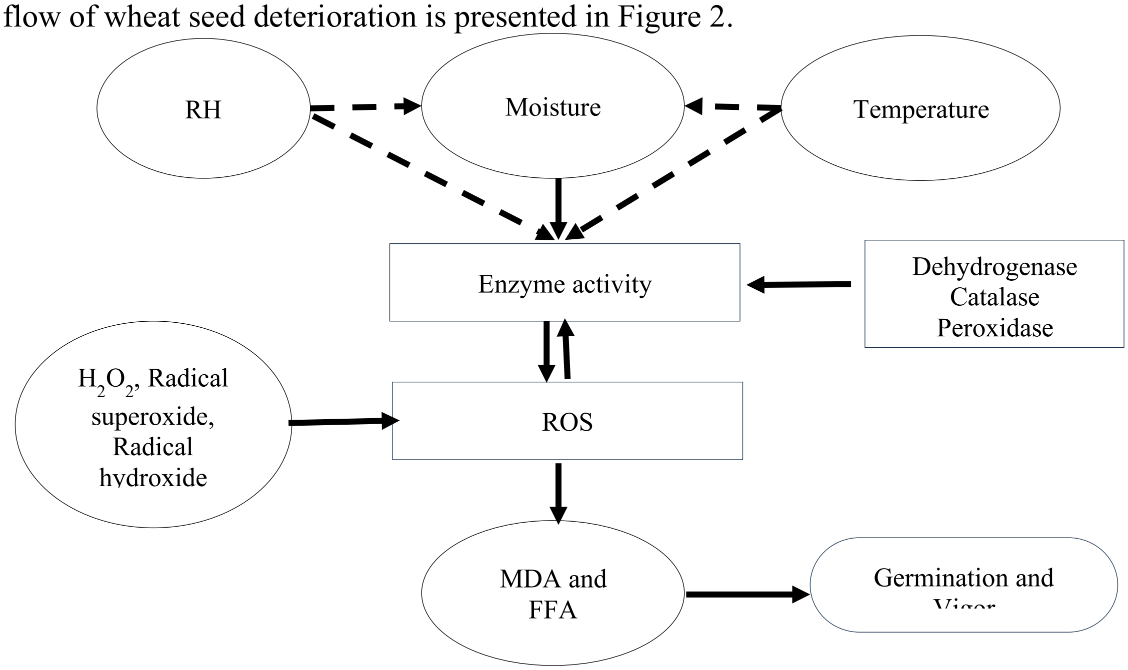

Figure 2. Flowchart of the wheat seed deterioration process.

4. Create models of wheat seed deterioration in the systems thinking experimental learning laboratory with animation (Stella) software.

The model was compiled based on a flowchart, followed by a determination of the quantitative relationship between components in the system. Quantitative and logical relationships obtained from literature studies and statistical analysis were included in the flowchart to form a model of process inputs and outputs. This relationship is in the form of a relationship between the pattern of physicochemical changes (internal factors) and changes in environmental factors (external factors) on wheat seed deterioration. Assembling variables in the system using Stella software (Stella 9.0.2) forms a Model Construction Layer (MCL). The relationship of mathematical equations in MCL was arranged in an Equation Layer (EL) (Noviana et al. 2017). Quantitative relationships between seed storage literature study components were assembled in the Model Construction Layer - Stella (MCL-S). MCL seed storage consists of the converter, connector, flow and stocks. The function of converter is to store constants, input equations, perform calculations from various other inputs or store data in graphical form (x and y tabulations), for example, packaging permeability input, RH out and temperature. The connector functions connect converters to converters, converters to flow and stocks to converters from the model. Flows that function to increase or decrease stocks, for example, changes in RH of metabolites. Stocks are described as the result of the accumulation of a mass flow.

5. Simulation and validation model.

Model simulation was carried out to determine the level of accuracy (logic) of the model that has been compiled so that the model's validity can be determined. The input used in the simulation consists of moisture content, initial viability, humidity and temperature. In addition, the simulation output consists of the moisture content, vigor and germination during storage period. Validation is intended as a stage of modeling activities which aims to assess the suitability of simulation results with actual results. Actual results were obtained from scientific journal data at the literature study stage. Model validation was carried out quantitatively using statistical tests (chi-square test), by comparing simulation results with actual results in the same storage period. Based on quantitative validation, the simulation results are declared appropriate or not different from the actual results if the chi-square value ≤ the chi-square table ($\alpha = 0.05$).

RESULTS AND DISCUSSION

The data on the physicochemical content of wheat seed

The physicochemical changes in seed deterioration during storage are complex processes. It includes protein denaturation, enzyme inactivation, membrane damage due to lipid peroxidation, and accumulation of toxic metabolites (Walters et al. 2010). During storage, the storage conditions affect the metabolism of wheat germ, where the metabolism may produce oxidative, toxic, and harmful compounds (Walters 1998). The enzymes involved in the metabolism of wheat seed during storage include dehydrogenase, catalase, and peroxidase (Dinelli and Lucchese 2003; Leggatt 2011; Peng et al. 2011; Tilebeni and Golpayegani 2011; Tian et al. 2019; Zhang et al. 2017). The data on physiochemical changes in wheat germ during storage are presented in Table 1. The changes in the content of dehydrogenase, catalase, peroxidase, H_2O_2, and germination followed a decreasing pattern with increasing shelf life, but in contrast to MDA and free fatty acids. These variables are variables that influence seed vigor during storage. Seed storage describes the process that occurs during seed storage, which begins with absorbing water vapor through the seed coat, thereby increasing the moisture content of the seed. An increase in seed moisture content causes the activation of the dehydrogenase enzyme so that the respiration process increases. Increasing the respiration process affects cell membrane damage, as cell leakage indicated. The increase in cell leakage, characterized by increasing MDA, affects the seed germination process, ultimately reducing seed vigor. These processes are influenced by RH and storage temperature, seed permeability, and the initial condition of the seeds before storage (initial seed vigor).

Table 1. The physiochemical content of wheat seeds during storage based on data in scientific journals.

Storage duration (weeks)	Dehydrogenase (U)	Catalase (mg/g min)	Peroxidase (U/g)	H_2O_2 (µmol/g)	MDA (µmol/g)	FFA (mg/100 g)	Germination (%)
0	0.210	0.550	1.40	0.210	8	18	98
1	0.200	0.425	1.10	0.190	7	19	70
2	0.170	0.190	0.70	0.180	9	20	55
3	0.050	0.150	0.50	0.170	10	23	15
4	0.035	0.120	0.40	0.158	11	25	12.5
5	0.025	0.100	0.35	0.121	12	28	10
6	0.020	0.080	0.30	0.110	13	30	7
7	0.015	0.050	0.24	0.105	13.4	42	4
8	0.015	0.050	0.24	0.100	13.6	58	0

Source: Peng et al. (2011); Tian et al. (2019); Zhang et al. (2017)

Pattern of physicochemical changes in wheat seeds during storage.

The deterioration of orthodox seeds generally occurs in three phases (Ebone et al. 2019). Phase I is the initial stage following harvest. This phase is characterized by the Amadori and Maillard reactions, which decrease the seeds' protection against oxidative damage (Murthy and Sun 2000). However, this phase does not significantly affect seed viability. Phase II marks the beginning of noticeable deterioration. During this phase, there is a reduction in the seeds' protective capacity against reactive oxygen species (ROS) and lipid peroxidation. This leads to membrane damage and the production of malondialdehyde (MDA) (Kibinza et al. 2006). Phase III involves significant changes, including a disruption of the mitochondrial membrane and increased respiration rate. This occurs due to decreased energy production per substrate and reduced electron transport efficiency (Xin et al. 2014). As respiration increases, the production of ROS also rises, creating an autocatalytic cycle that exacerbates lipid peroxidation. Consequently, genetic material suffers increased damage, ultimately leading to complete inhibition of germination (Klein et al. 2017; Koskosidis et al. 2022).

In this model of wheat seed deterioration, it is predicted that the process can be divided into two critical phases after the seeds reach physiological maturity. This phase is the phase of decreased enzyme activity responsible for the degradation of ROS (phase I) and the phase of membrane damage, consumption reserves, and damage to genetic material (phase II). The storage duration of seed wheat affects enzymes' activity (dehydrogenase, catalase, and peroxidase). These enzymes are simultaneously influenced and affect ROS, which is also involved in the H_2O_2 content. The accumulation of these free radicals affects MDA production and free fatty acids, finally decreasing seed germination.

a. Mathematical model of changes in enzyme activity in wheat seed during storage

   Enzymes that influence the deterioration of wheat seeds during storage include dehydrogenase, catalase, and peroxidase. Dehydrogenase plays a vital role in the metabolism of organic compounds and is closely associated with the vigor of wheat germ. In contrast, catalase and peroxidase are defensive enzymes that help eliminate hydrogen peroxide (H_2O_2) and free radicals. A decline in the physiological quality of seeds, known as seed decline, is indicated by the inactivation of antioxidant enzymes responsible for degrading reactive oxygen species (ROS). The equation for the effect of storage duration on changes in enzyme activity is as follows:

Dehydrogenase = 0.0203465 + (0.201017 - 0.0203465) / (1 + exp(7.47849 x ln('storage duration' / 2.45186))) (Fig. 3).
Catalase = -0.124125 + (3.12787 + 0.124125) / (1 + exp(0.609802 x ln("storage duration' / 0.0621322))) (Fig. 4).
Peroxidase = 0.0728109 + (2.22881 - 0.0728109) / (1 + exp(1.16467 x ln('storage duration' / 0.922842))) (Fig. 5).

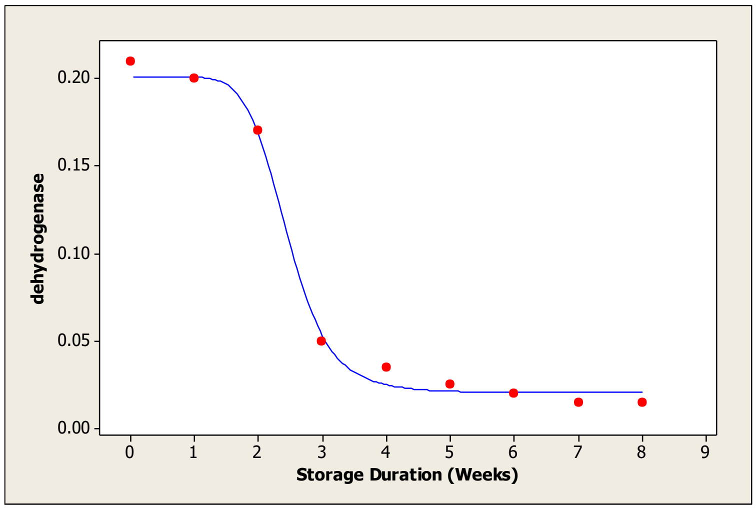

Figure 3. Graph of the storage duration effect on changes in dehydrogenase.

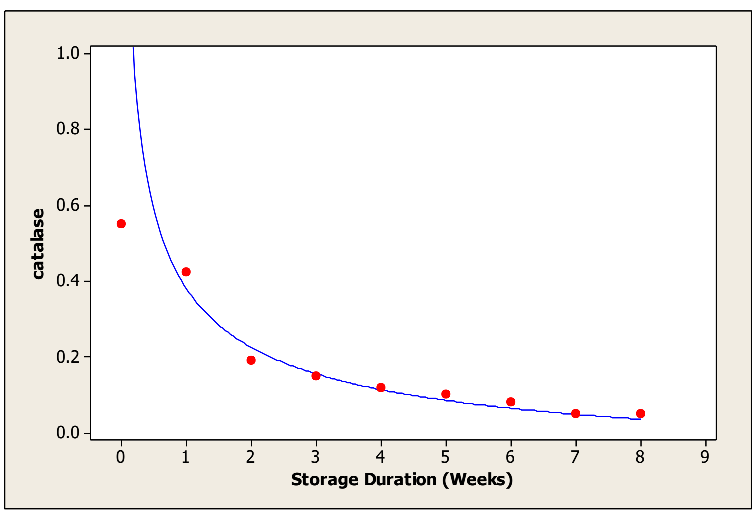

Figure 4. Graph of the storage duration effect on changes in catalase.

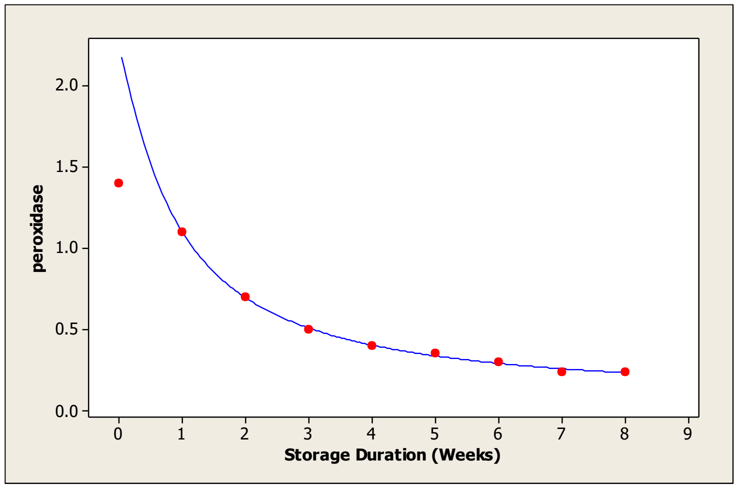

Figure 5. Graph of the storage duration effect on changes in peroxidase.

The relationships between components in the system are obtained through regression analysis (linear or non-linear). Quantitative relationships between components in the system are needed to build logical processes in the model. The equation used to build a wheat seed deterioration model is the seed viability equation.

b. Mathematical model of enzyme activity effect on ROS and H_2O_2

The mathematical model between enzyme activity on ROS and H_2O_2 is expressed in the following equation:

Enzyme activity = ROS + (Dehydrogenase + Catalase + Peroxidase/3) x (RH/40) x (Temperature/50)

ROS(t) = ROS(t - dt) + (-H_2O_2) x dt

H_20_2 = ROS x Changes index of H_2O_2

In the journal used as reference data, it is stated that the RH and temperature of the storage room are constant, namely 40 and 50 ^{0}C, respectively. The high temperature used is a factor for rapid aging.

c. Mathematical model of the effect of H_2O_2 on MDA and free fatty acids

There was an increase in the contents of MDA and free fatty acids. MDA is a by-product of lipid peroxidation, which is the primary cause of membrane damage. MDA = 4.62271 + (18.4012 - 4.62271) x exp(-22.2767 $H_20_2{}^{1.70613}$) (Fig. 6). FFA = 123.336 x exp (-10.1865 x H_20_2) (Figure 7). From Figures 6 and 7, it can be seen that there was an increase in the content of MDA and free fatty acids.

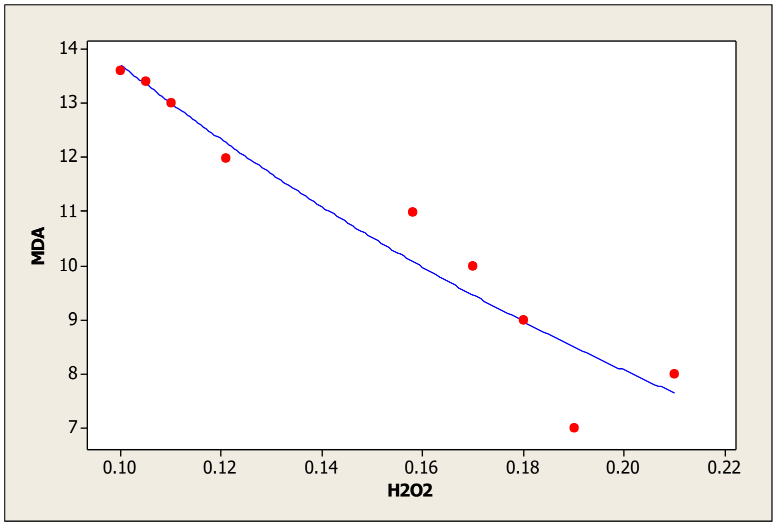

Figure 6. Graph of the effect of changes in H_2O_2 in MDA.

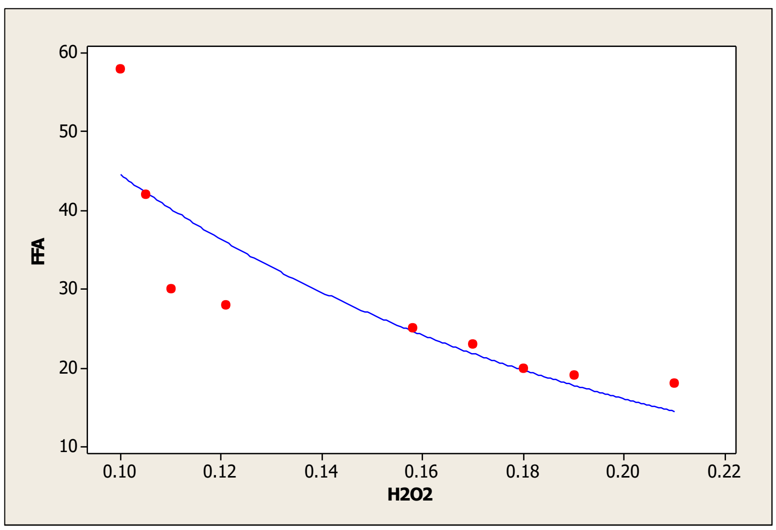

Figure 7. Graph of the effect of changes in H_2O_2 in FFA.

d. Mathematical model of the effect of MDA on germination

Membrane damage is indicated increasing in MDA content, which causes a decrease in germination. The equation for the relationship between MDA and germination rate is as follows: Germination = 2.30234 + (109.524 - 2.30234) / (1 + exp(11.4657 x ln('MDA' / 9.39342))) (Figure 8).

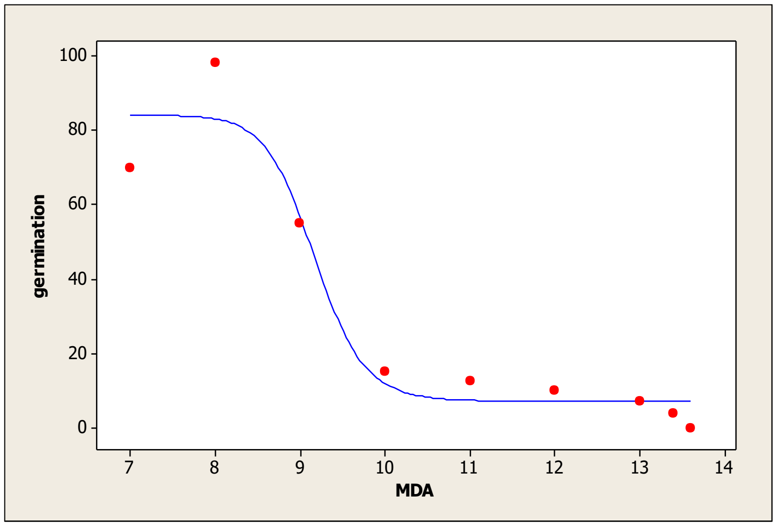

Figure 8. Graph of the effect of MDA changes in seed germination

A flowchart of the process of wheat seed deterioration.

The wheat seed deterioration flowchart describes the processes in the seed deterioration system, which begins with the absorption of moisture content, which influences other metabolic processes in the seed, causing a decrease in seed vigor and storability. In this study, the flowchart of wheat seed deterioration is shown in Figure 9. Next, the flowchart is used to develop a system model of wheat seed deterioration.

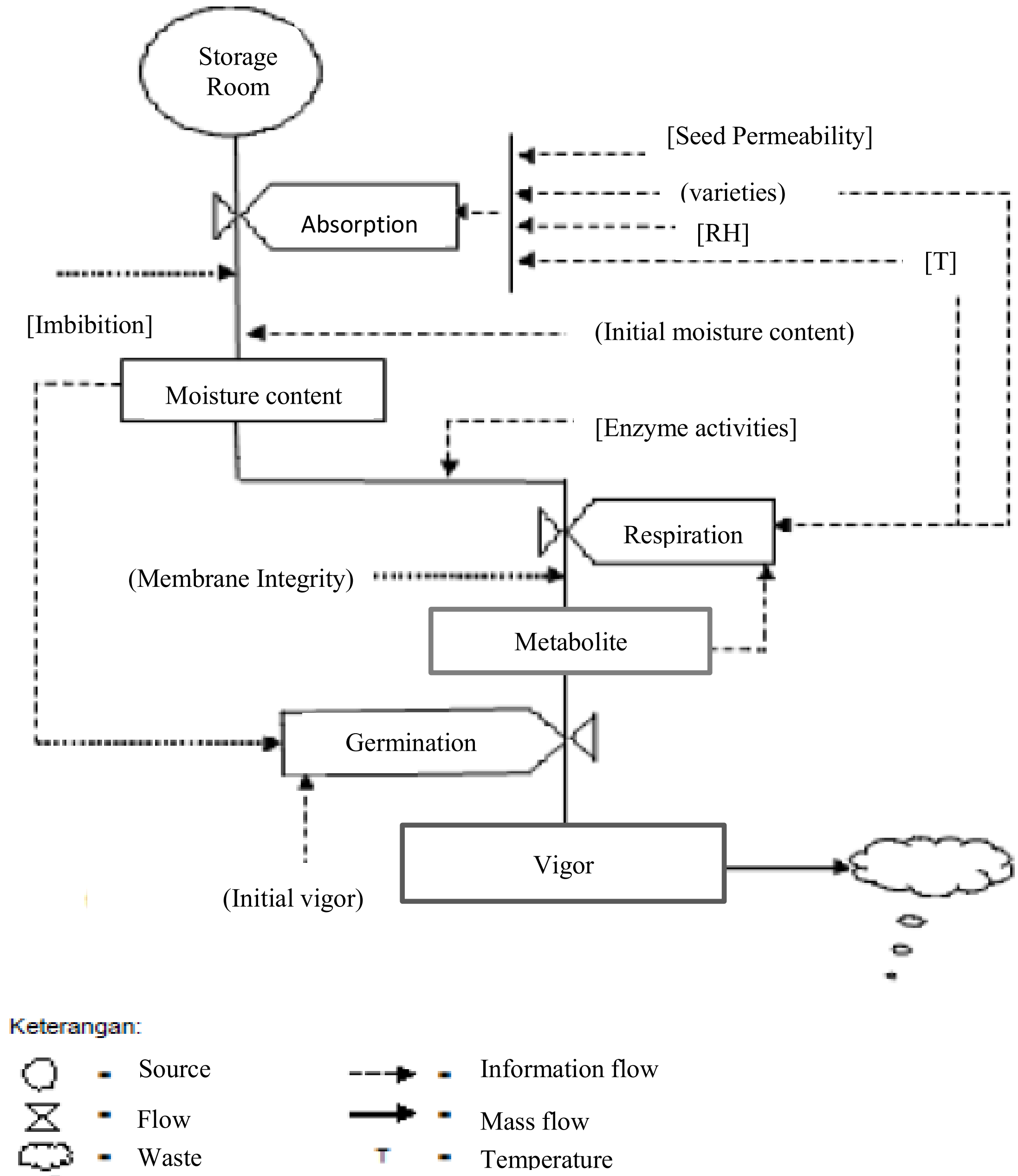

Figure 9. The flowchart of wheat seed deterioration during storage

Model of wheat seeds deterioration in the Systems Thinking Experimental Learning Laboratory with Animation (Stella) software.

The quantitative relationships between components from the literature are arranged in the Model Construction Layer - Stella (MCL-S), which refers to the research of Wahyuni et al. (2015) with modifications. MCL-S for the wheat seed storage dynamic model is described in Figure 10.

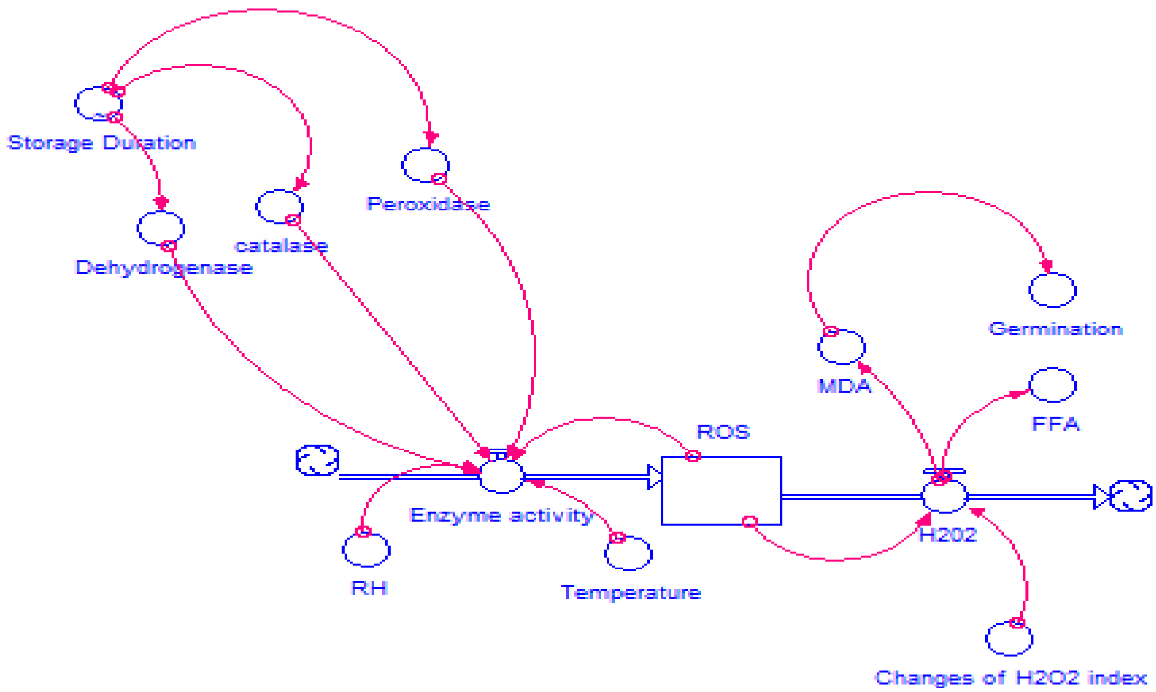

Figure 10. Model Construction Layer-Stella (MCL-S) of wheat seed deterioration.

Simulation and validation model.

The estimation of wheat seed deterioration based on systems approaches using Stella software revealed an alteration in the concentration of dehydrogenase, catalase, peroxidase, H_2O_2, and germination. A decreasing pattern with increasing storage duration further follows this. However, it does not appear in the MDA and free fatty acid variables (Tables 2 & 3). This is to the data in the scientific journal. These changes are a system that processes simultaneously, affecting wheat seeds' vigor and germination. The equations in the Stella program are presented as follows:

Table 2. Changes in the physiochemical content of wheat seed stored at 50 ^{0}C based on the results of the estimation using the Stella program

Weeks	Dehydrogena	catalase	Peroxidase	Enzyme activi	H202	MDA	FFA	Germination	
0	0.20	3.06	2.23	6.01	0.20	7.92	16.08	96.24	
1	0.20	0.38	1.10	2.75	0.18	8.79	19.71	75.24	
2	0.17	0.23	0.70	2.25	0.16	9.70	23.68	46.12	
3	0.05	0.16	0.51	1.84	0.15	10.61	27.93	23.62	
4	0.02	0.11	0.40	1.59	0.13	11.49	32.40	12.01	
5	0.02	0.09	0.34	1.40	0.12	12.32	37.04	6.88	
6	0.02	0.06	0.29	1.25	0.11	13.10	41.77	4.63	
7	0.02	0.05	0.26	1.11	0.10	13.80	46.55	3.59	
8	0.02	0.04	0.23	1.00	0.09	14.44	51.31	3.07	
9	0.02	0.04	0.23	0.91	0.08	15.00	56.02	2.80	
Final	0.02	0.04	0.23					2.65	

Table 3. Changes in the physiochemical content of wheat seed stored at 25 ^{0}C based on the results of the estimation using the Stella program

Weeks	Dehydrogena	catalase	Peroxidase	Enzyme acti	H202	MDA	FFA	Germination
0	0.20	3.06	2.23	10.02	0.20	5.92	16.08	99.24
1	0.20	0.38	1.10	3.70	0.18	6.79	19.71	98.04
2	0.17	0.23	0.70	2.87	0.16	7.70	23.68	96.05
3	0.05	0.16	0.51	2.21	0.15	8.61	27.93	93.08
4	0.02	0.11	0.40	1.86	0.13	9.49	32.40	89.10
5	0.02	0.09	0.34	1.62	0.12	10.32	37.04	84.27
6	0.02	0.06	0.29	1.43	0.11	11.10	41.77	78.93
7	0.02	0.05	0.26	1.27	0.10	11.80	46.55	73.45
8	0.02	0.04	0.23	1.13	0.09	12.44	51.31	68.18
9	0.02	0.04	0.23	1.04	0.08	13.00	56.02	63.35
Final	0.02	0.04	0.23					59.06

Equation on the Stella program:

```
ROS(t) = ROS(t - dt) + (- H202) * dt
INIT ROS = 2
OUTFLOWS:
    H202 = ROS*Changes_of_H2O2_index
UNATTACHED:
    Enzyme_activity = ROS+(Dehydrogenase+catalase+Peroxidase/3)*(RH/40)*(Temperature/50)
catalase = -0.124125 + (3.12787 + 0.124125) / (1 + EXP(0.609802 * LOGN(Storage_Duration /
0.0621322)))
Changes_of_H2O2_index = 0.1
Dehydrogenase = 0.0203465 + (0.201017 - 0.0203465) / (1 + EXP(7.47849 * LOGN(Storage_Duration /
2.45186)))
FFA = 123.336 * EXP (-10.1865 *H202)
Germination = 2.30234 + (109.524 - 2.30234) / (1 + EXP(11.4657 * LOGN(MDA / 9.39342)))
MDA = 4.62271 + (18.4012 - 4.62271) * EXP(-22.2767 * H202 ^ 1.70613)
Peroxidase = 0.0728109 + (2.22881 - 0.0728109) / (1 + EXP(1.16467 * LOGN(Storage_Duration/
0.922842)))
RH = 40
Temperature = 50
Storage_Duration = GRAPH(TIME)
(0.00, 0.0001), (1.00, 1.00), (2.00, 2.00), (3.00, 3.00), (4.00, 4.00), (5.00, 5.00), (6.00, 6.00), (7.00, 7.00),
(8.00, 8.00)
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Data on changes in the physicochemical content of wheat seed based on the results of estimation using the Stella program, then validation of the data results was carried out. Validation was carried out using the chi-square test approach, where the estimated results using Stella program were compared with data in scientific journals. Model validation aims to determine the degree of suitability between the simulation results and the actual results. Conformity assessment is based on data from simulation results within the actual results' confidence interval (1-α = 0.95) (Wahyuni et al. 2015; Noviana et al. 2017). In addition, a model that employs a systems approach using software can be considered valid if the calculated chi-square value is less than the value found in the chi-square table (Ouyang et al. 2010). If this condition is met, the results obtained from the estimation using Stella software can be deemed valid and applicable. Specifically, when the chi-square test results indicate that the calculated chi-square value is smaller than the table value, it suggests that the simulated data aligns closely with the actual results. The validation process demonstrates a strong concordance between the simulation outcomes and the actual results for all variables (Tables 4-10). Consequently, the developed deterioration model is capable of predicting the physiochemical changes in wheat seeds during storage.

Table 4. Validation of changes in the dehydrogenase content of wheat seed based on estimation with the Stella program and data in scientific journals.

Storage duration (week)	Dehydrogenase		Chi-square value	Chi-square table
	Stella	scientific journal		
0	0.200	0.210	0.0112	15.507
1	0.200	0.200		
2	0.170	0.170		
3	0.050	0.050		
4	0.020	0.035		
5	0.020	0.025		
6	0.020	0.020		
7	0.020	0.015		
8	0.020	0.015		

Table 5. Validation of changes in the catalase content of wheat seed based on estimation with the Stella program and data in scientific journals.

Storage duration (week)	Catalase		Chi-square value	Chi-square table
	Stella	scientific journal		
0	3.060	0.550	11.477	15.507
1	0.380	0.425		
2	0.230	0.190		
3	0.160	0.150		
4	0.110	0.120		
5	0.090	0.100		
6	0.060	0.080		
7	0.050	0.050		
8	0.040	0.050		

In this study, germination decreased with increasing storage time and followed a sigmoid pattern. This shows that wheat seed deterioration is generally caused by two main processes: the inactivation of antioxidant enzymes and cell membrane damage, which are interrelated and depicted following a sigmoid pattern. This is in accordance with research by Walter et al. (2010), seed deterioration was described by a sigmoid correlation between viability and time, although seed vigor, even though did no significant change was found on seed vigor, but the rate of seed death was faster. This study described the decrease in germination power using an exponential equation. This aligns with research by Suryati et al. (2018) that soybean seeds' germination followed a sigmoid pattern with an exponential equation. The estimation of wheat seed deterioration using system approaches with the Stella program indicates that a decrease in the content of dehydrogenase, catalase, and peroxidase characterizes the inactivation of antioxidant enzymes. This inactivation serves as an indicator of reduced physiological quality in seeds, which is a sign of seed deterioration. Dehydrogenase is an enzyme involved in the metabolism of organic compounds and is closely linked to the vigor of wheat seeds. Catalase and peroxidase are defensive enzymes that help remove H_2O_2 and ROS. Meanwhile, increasing MDA and fatty acids content indicates cell membrane damage. The compositional changes due to lipid peroxidation lead to extensive membrane damage and open pores. So it causes loss of ionic homeostasis and membrane integrity and disrupts proteins attached to the membrane.

Table 6. Validation of changes in the peroxidase content of wheat seed based on estimation with the Stella program and data in scientific journals.

Storage duration (week)	Peroxidase		Chi-square value	Chi-square table
	Stella	scientific journal		
0	2.230	1.400	0.495	15.507
1	1.100	1.100		
2	0.700	0.700		
3	0.510	0.500		
4	0.400	0.400		
5	0.340	0.350		
6	0.290	0.300		
7	0.260	0.240		
8	0.230	0.240		

Table 7. Validation of changes in the H_2O_2 content of wheat seed based on estimation with the Stella program and data in scientific journals.

Storage duration (week)	H_2O_2		Chi-square value	Chi-square table
	Stella	scientific journal		
0	0.200	0.210	0.012	15.507
1	0.180	0.190		
2	0.160	0.180		
3	0.150	0.170		
4	0.130	0.158		
5	0.120	0.121		
6	0.110	0.110		
7	0.100	0.105		
8	0.090	0.100		

Table 8. Validation of changes in the MDA content of wheat seed based on estimation with the Stella program and data in scientific journals.

Storage duration (week)	MDA		Chi-square value	Chi-square table
	Stella	scientific journal		
0	7.92	8.00	0.645	15.507
1	8.79	7.00		
2	9.70	9.00		
3	10.61	10.00		
4	11.49	11.00		
5	12.32	12.00		
6	13.10	13.00		
7	13.80	13.40		
8	14.44	13.60		

Table 9. Validation of changes in the FFA content of wheat seed based on estimation with the Stella program and data in scientific journals.

Storage duration (week)	FFA		Chi-square value	Chi-square table
	Stella	scientific journal		
0	16.08	18.00	12.957	15.507
1	19.71	19.00		
2	23.68	20.00		
3	27.93	23.00		
4	32.40	25.00		
5	37.04	28.00		
6	41.77	30.00		
7	46.55	42.00		
8	51.31	58.00		

Table 10. Validation of changes in the germination of wheat seed based on estimation with the Stella program and data in scientific journals

Storage duration (week)	Germination		Chi-square value	Chi-square table
	Stella	scientific journal		
0	96.24	98.00	8.648	15.507
1	75.24	70.00		
2	46.12	55.00		
3	23.62	15.00		
4	12.01	12.50		
5	6.88	10.00		
6	4.63	7.00		
7	3.59	4.00		

8	3.07	0.00

CONCLUSIONS

Estimation of wheat seed deterioration can be predicted through a systems approach. Deterioration estimation is a system or process model involving many interrelated variables simultaneously. The following equations can estimate the wheat seed deterioration model: dehydrogenase = 0.0203465 + (0.201017 - 0.0203465) / (1 + exp (7.47849 x ln ('storage duration' / 2.45186))); catalase = -0.124125 + (3.12787 + 0.124125) / (1 + exp (0.609802 x ln ('storage duration' / 0.0621322))); peroxidase = 0.0728109 + (2.22881 - 0.0728109) / (1 + exp (1.16467 x ln ('storage duration'/0.922842))); enzyme activity = ROS + (Dehydrogenase + Catalase + Peroxidase/3) x (RH/40) x (Temperature/50); ROS(t) = ROS(t - dt) + (-H_2O_2) x dt; H_2O_2 = ROS x Changes index of H_2O_2; MDA = 4.62271 + (18.4012 - 4.62271) x exp (-22.2767 x $H_20_2^{1.70613}$); FFA = 123.336 x exp (-10.1865 x H_20_2); germination = 2.30234 + (109.524 - 2.30234) / (1 + exp (11.4657 x ln ('MDA' / 9.39342))). During storage, antioxidant enzymes responsible for degrading reactive oxygen species (ROS) become inactive. The accumulation of ROS leads to membrane damage, which subsequently reduces seed vigor, resulting in decreased germination rates. Dynamic models of seed storage can help predict the deterioration of wheat seeds. The inputs for these models include initial moisture content, initial seed viability, humidity, and storage room temperature

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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