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DYNAMIC MODEL OF SEED GERMINATION ON THE EXAMPLE OF A GENUS *Dracocephalum* L. BASED ON LOGISTIC FUNCTION

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ABSTRACT. The aim of this paper is to present the use of mathematical model for an assessment of seed germination on the example of a genus *Dracocephalum* L. based on logistic function. An assessment of the quality of seeds and their species specificity was carried out. For this the method of a mathematical model of seed germination and the "Origin Pro" application package was used. The objects of research were samples of species *Dracocephalum* L. of different geographical origin from the collection of the I.N. Vavilov named All-Russian Crop Research Institute (VIR). Morphometric parameters of seeds of the studied species of the genus *Dracocephalum* L. were identified, which were divided into two groups. The first group with small seeds (2.7–3.0 mm long and 1.6–2.0 mm wide) included varieties of the species *D. moldavica*, and the second group – with very small seeds (2.0 mm in length and 1.0 mm wide) of *D. multicaule* and *D. nutans*. To assess the quality of seeds, we used both standard static indicators for germination, germination energy and seed vigour which are also assessed by both known the Grodzinsky bio test, and new ones based on dynamic parameters for evaluating seed germination. The dynamic model presented in the work reproduces changes in the initial phase of plant growth through the dynamics of seed germination. That is, the change in the state of a living object in motion in this model. When processing the results, a logistic function was applied that reflects the dynamics of change or accumulation of quantitative signs with the transition to new qualitative indicators. It was revealed that the shortest germination time of half of the maximum number of germinated seeds (intensity of germination) equal to 44.0 hours had the sample K-6 ('Aroma-2'). This indicates vigourous and friendly germination of the seeds of this variety. For sample K-7 ('Aroma-2'), this figure is 60 hours and, therefore, the germination rate is less than that for K-6. Similar in these parameters and the intensity of germination in the sample K-8 'Zeya' equal to 53 hours. Sample K-10 ('Arhat') was characterized by a relatively high germination rate, intensity of germination equal to 46 hours. Samples at 32 (*D. nutans*) and at 20 (*D. multicaule*) had approximately the same intensity of germination was equal to 61 and 54 hours, respectively. As a result, comparing the similarly different age characteristics of the seed material, a certain species and variety specificity in the dynamics of growth processes in the seeds of various types of snake head was revealed. The novelty of these studies was the search for new patterns and phenomena in assessing the quality of seeds and their species specificity.

Introduction

It is known that one of the important problems in crop production is the assessment of the quality of planting material, and in the field of agriculture – assessment of the quality of soil and agricultural technologies using bio tests (McDonald, 1998; Komarov, 2002, Nugis *et al.*, 2021). The existing criteria for assessing the quality of seed material are mainly based on determining the indicators of their germination and germination energy (Perry, 1978; Taylor, 2003). Laboratory germination and germination energy are measured by germinating seeds on substrates or on sand in growers with strictly regulated environmental conditions for a fixed time for each type of seed. That is, these scoring parameters are based on standard static metrics. So, for example, for common wheat (*Triticum vulgare* L.). Host germination energy is determined on the 3rd day, and the germination capacity on the 7th day (Hampton, 2002).

As our early research showed (Komarov, 2002), one of the most informative indicators of seed quality based on static indicators is the assessment of seed vigour. The essence of this method, also known as the method of biological samples (Grodzinsky bio test), is described in detail by the author himself (Grodzinsky, 1991). This indicator was used to assess a number of crops, including – *Carthamus tinctorius* L. (Ghassemi-Golezani *et al.*, 2016); *Brassica napus* L. (Amirmoradi, Feizi, 2017; Gu *et al.*, 2019), *Oryza sativa* L. (Ibrahim, Ikhajiagbe, 2021), *Zea mays* L. (Han *et al.*, 2018) and others. An assessment of the influence of various factors on the germination of seeds of various plants is also shown in the works of (Baghel *et al.*, 2019), both for maize seeds (*Zea mays* L.) and for other citation species (Sabelli, Larkins, 2015; Wei, Huang *et al.*, 2018). However, all these methods have one thing in common, which is that the assessment of both the strength of growth and germination is based on static indicators. That is, these estimates are fixed by the time the indicator is determined which contradicts the dynamics of the development of living matter, such as the seeds of living plants. In this regard, the opinion was formed (McDonald, 1998; McDonald, 1999; Ellis, Roberts, 1980; Hampton, 2002) that it is almost impossible to develop any standard methods for assessing the quality of plant seeds for various reasons (prolonged ripening and germination periods, the presence of a dormant period, ecological diversity of species, *etc*.). For these reasons, the quality and viability of seeds of various species have to be determined empirically for each batch of seeds, both immediately before sowing and at various stages of storage. Such routine, but necessary activities, require colossal time and money, limit the creative potential in the search for new patterns and phenomena (Anikina *et al.*, 2021).

At the same time, seeds are living organisms and for them (as for all living organisms) a change in state over time is inherent (growth rate, growth force, germination energy and even germination). Therefore, it would be very tempting to move from static indicators to dynamic ones, which describe the change in the state of the biological system (seed) in time. To substantiate the transition from static to dynamic indicators of seed germination was used. The purpose of these studies was (using the example of the genus *Dracocephalum* L.) to assess the possibility of using a dynamic method for assessing seed germination. To determine the species specification of the genus *Dracocephalum* L., the transition from static to new dynamic parameters were presented. The presented model reveals the possibilities for the development of a method for assessing the quality of seeds of other crops.

Methods

Concerning determination of the bio test parameters a sufficiently large number of seeds (100–200 paces) were used (Grodzinsky, 1991). The seeds were placed in Petri dishes. The bottom of the dishes was previously covered with a layer of filter paper. The seeds evenly placed on the surface of the cup with distilled water were moistened. The volume of water was determined by the number and weight of the analysed test plants. Once the seeds had germinated, the interval between the counting of seeds of each batch was counted which were selected taking into account the intensity of their initial germination processes. The counting of germinated seeds until 50% germinated in the control variant (seed treatment with water) was carried out. The conditions and method of the experiment were based on the assessment of both the parameters of standard static indicators of seed germination and using a dynamic model of seed germination. The parameters of standard static indicators of seed germination by the International Seed Testing Association – ISTA (ISTA, 2021; Handbook, 1995) were developed.

The most common test for germination and seed germination energy as the main parameter of static indicators was used. In addition to standard methods for assessing the dynamic indicators of seed germination was used (Vitkovskaya, 2015; Chetyrbotskiy, Chetyrbotskiy, 2020).

The experiment to assess the dynamics of seed germination was set up in accordance with various regulations (ADSA, 1993; Handbook, 1995; ISTA, 2021). The objects of research were samples of *Dracocephalum* L. species of different geographic origin from the collection of the VIR (All-Russian Crop Research Institute) (Table 1). Since the sizes of seeds in the species of the snake head *Dracocephalum* L. is differ, therefore, they were conditionally divided into two groups. The first group with small seeds (2.7–3.0 mm long and 1.6–2.0 mm wide) includes *D. moldavica* varieties. The mass of 1000 seeds of these varieties is 1.79–2.28 g.

The second group with very small seeds (2.0 mm in length and 1.0 mm in width) includes the species *D. multicaule* and *D. nutans*. The mass of 1000 seeds ranged from 0.54 to 0.65 g.

The evaluated seeds for germination were treated (soaked) with 5–10 ml of distilled water. For example, for small-seeded plants such as Moldavian snake head is 5 ml per 100 paces plants, but for larger (cereals) is 10 ml. To characterize the quality of seeds, various indicators were used. The most important of above were germination, germination energy, seed moisture, seed purity and category were also taken into account. Seed category – original seeds, elite, and reproduction. The seeds of Moldavian snakehead specimens belonged to the reproduction category (1–3 generations), varietal purity was 95%, and moisture content was 12%. The germination and germination energy of the samples was established in the course of the experiment.

From a mixture of seeds, samples were taken four replicates of 100 paces placed in Petri dishes on filter paper Petri dishes in a thermostat at the optimum germination temperature for seeds of the analysed species were placed. Petri dishes were preliminarily washed with hot water and detergent, rinsed with 1% potassium permanganate solution, then with distilled water and alcohol. Each dish was labeled with sample, replication, start date, and counting dates. The accounting was carried out manually, after 2–6 hours. A variable temperature was created in the thermostat of 20 °C – 18 h, 30 °C – 6 h.

The method for assessing the dynamic indicators of seed germination were used. As soon as the seeds germinated, the calculation and assessment of the dynamic indices of seed germination were made. The interval between the counting of seeds of each batch was chosen taking into account the intensity of their initial germination processes every 2–6 hours. To implement the mathematical model of seed germination the Origin Pro software package available to every user of a personal computer was used. The results were processed using MS Excel 2003.

For evaluating of the seed germination which as the basis for processing the results for that a logistic function was used. It should be indicated that in the dynamics of change or accumulation of quantitative indicators the transition to new qualitative indicators is reflected. The logistics function was described by the following formula (Komarov *et al.*, 2007):

$$N = \frac{N_{max}}{1 + e^{-\frac{t-t_c}{t_k}}}, \qquad (1)$$

where N – number of germinated seeds at time (t);
t – the time during which a certain number of seeds germinate, expressed in%;
N_{max} – maximum number of germinated seeds;
t_k – the rate of increase in the number of germinated seeds,
t_c – the time at which the number of germinated seeds is equal to half of the maximum number of germinated seeds (which reflects the intensity of germination).

By the germination energy, we meant a fixed period for each plant species without taking into account their variety-specificity. So, the germination energy of the Moldavian snake head on the 3rd day was determined. The seed germination energy under the conditions of this experiment was characterized in the dynamics of the entire period of the experiment. Its was displayed by the *tc* index and in essence which was characterized the intensity of growth processes. Seed quality indicators taking into account their species and varietal heterogeneity or specificity were assessed.

The statistical estimation of data of the areas of germination energy, intensity of germination (*tc*) and speed of seed germination (k) has been carrying out by Student t-test at 0.05 levels.

Results

The morphometric parameters of the seeds of the studied species of the genus *Dracocephalum* L. are shown in Table 1. It should be emphasized that the peculiarity of the structure of the *Lamiaceae* L. fruit to some extent predetermines the specifics of the system for assessing the quality of the seeds of this plant. Seed in these species is not released from pericarp, which performs a protective function, which probably has a certain effect on the qualitative characteristics of seeds, including the intensity of their germination.

Morphometric study of *Eremus* L. showed that their sizes differ in *Dracocephalum* L. species. Thus, dividing them into two different groups was quite justified. Indicators for assessing the quality of seeds obtained as a result of laboratory experiments are shown in Table 2.

Table 1. Morphometric parameters of the seeds for species of the genus *Dracocephalum* L.

No in order	Kind & variety	No. sample according to the VIR catalog	Genesis	Weight of 1000 seeds, g	Seed size, mm	
					length	width
1	*D. moldavica* – Moldavian snakehead, variety Arhat	K-10	St. Petersburg	1.91	2.8	1.6
2	*D. moldavica* – Moldavian snakehead, variety Aroma-2	K-6	Moldova	2.28	3.0	1.9
3	*D. moldavica* – Moldavian snakehead, variety Aroma-2	K-6	Germany	1.86	2.7	1.7
4	*D. moldavica* – Moldavian snakehead, variety Zea	K-7	Kazakhstan	1.79	3.0	2.0
5	*D. multicaule* – Multi-stemmed, snakehead	K-7	Kazakhstan	1.79	3.0	2.0
6	*D. multicaule* – Multi-stemmed, snakehead	Bp-20	Germany	0.54	2.0	1.0
7	*D. nutans* – Hovering snakehead	Bp-32	Switzerland	0.65	2.0	1.0

Table 2. Indicators for assessing the quality of seeds in a dynamic model

No in order	Kind & variety	Germination energy, %	Laboratory germination, %	t_c, h	t_k, h	$t_c\, t_k^{-1}$	k, h^{-1}	R^2
1	*D. moldavica* – Moldavian snakehead, variety 'Arhat'	76 ± 2	78 ± 2	46 ± 0.6	7.05	6.5	0.14 ± 0.01	0.99
2	*D. moldavica* – Moldavian snakehead, variety Aroma-2	77 ± 2	79 ± 2	44 ± 0.6	12.9	3.4	0.08 ± 0.01	0.98
3	*D. moldavica* – Moldavian snakehead, variety Aroma-2	57 ± 1	64 ± 1	60 ± 0.9	15.2	4.2	0.07 ± 0.01	0.99
4	*D. moldavica* – Moldavian snakehead, variety Zea	68 ± 2	72 ± 2	53 ± 1.0	14.7	3.6	0.07 ± 0.003	0.99
5	*D. multicaule* – Multi-stemmed snakehead	87 ± 2	93 ± 2	54 ± 2.0	4.5	13.5	0.22 ± 0.01	0.99
6	*D. nutans* – Hovering snakehead	83 ± 2	88 ± 2	61 ± 0.5	5.9	10.3	0.17 ± 0.01	0.99

$t_c\, t_k^{-1}$ – dynamic growth rate of germinated seeds; k – the speed of seed germination; R^2 – coefficient of determination; digits with plus and minus are the standard deviation of data ($P < 0.05$).

It is known that the germination rate of seeds is determined by the peculiarity of their cultivation, duration and storage method including genetic, qualitative traits and other. According to standard indicators (germination), the best indicators with a sample from Germany *D. multicaule* L. – Multi-stemmed snake head (germination rate 93%) were obtained. Somewhat lower (germination rate 88%) or a sample from Switzerland *D. nutans* – Hovering snake head was recorded. Both of these samples are perennial and small-seeded species (0.54–0.65 g per 1000 seeds). For larger-seeded and annual species *D. moldavica* L. – Moldavian snake head, the following row of germination was formed: 79% – sort 'Aroma-2' (Moldova), 78% – sort 'Arhat' (St. Petersburg), 72% – variety 'Zea' (Kazakhstan), 64% – variety 'Aroma-2' (Germany). The germination energy index in a similar way was distributed. The most significant 87% and 83% were for perennial samples No. 5 and No. 6. At the same time, variety 'Arhat' – 76%, 'Aroma-2' (Moldova) – 77%, 'Zea' – 68%, 'Aroma-2' (Germany) – 57%. However, these indicators of germination and germination energy were only to some extent associated with crop yield (Lavrukov, 2012) and do not provide the necessary information content.

Discussion

The dynamic indicators where a mathematical model of seed germination of the genus *Dracocephalum* L. implemented on the basis of a logistic function, provides great information content in terms of seed quality and potential yield we used. Analysis of the model's operation shows (Table 2 and Fig. 1) that according to the tc indicator the germination time of half of the maximum number of germinated seeds is established. The presented tc indicator is very close to the (seed vigour) indicator or the Grodzinsky bio test (Grodzinsky, 1991). It differs in that the tc index determines the LD50 index (50% of germination) relative to all germinated seeds, while the seed vigour index or Grodzinsky bio test determines the LD50 index from the total volume of seeds which includes both germinated (germination) and non-germinated (100% – germination) seeds.

It was found that sample No. 2 ('Aroma-2') had the smallest tc equal to 44.0 hours. Sample No. 1 was somewhat inferior in this indicator germinating by 50% in 46 hours. This indicates vigourous and friendly germination of seeds of these varieties. In addition, this indicator determines the intensity of growth and can become the basis for a preliminary assessment of the potential yield of plants. For sample No. 4 ('Zea'), this figure is 53 hours and for perennial sample No. 5 – 54 hours. The samples No. 3 (60 hours) and No. 6 (61 hours) turned out to be the most "slow" in seed germination.

The dynamics of the process of seed germination is characterized by the speed of germination, acceleration of germination and can be displayed by the angle of inclination on the graph (Fig. 1). Moreover, the larger and steeper the angle of inclination (attack), the more intense the initial stage of growth processes. Indicator k characterizes the rate of seed germination where $1 / k = t_k$ is a value which characterizes the physiological process of growth. At the same time, the physiological postulate is accepted that the less time is required for seed germination and the more intensive the germination process. In terms of t_k, the following features are noted. The smallest t_k value was observed for perennial samples No. 5 = 4.5 hours and No. 6 = 5.9 hours. Annual samples were significantly inferior in physiological parameters of germination where t_k varieties 'Arhat' = 7.05 hours, 'Aroma 2' = 12.9 (sample 2) and 15.2 (sample 3). 'Zea' was almost the "slowest" cultivar where t_k = 14.7 hours.

It is important to note that when describing the dynamic model of germination, very significant statistical indicators are displayed (Table 2, Fig. 1). Thus, the coefficient of determination R^2 for all variants of seed germination was not lower than 0.98. It explains the ability of regression, *i.e.* shows what fraction of the variation (variance) is described by the constructed model. Thus, according to R^2, one can judge how well the constructed model fits the available data and how close the true observations lie to this model.

An important circumstance is that the species of the genus *Dracocephalum* L. from the *Lamiaceae* L. family are not only annuals but also perennial herbaceous plants. Consequently, their seeds can differ morphologically, the type of dormancy, the nature of germination, viability, the duration of its preservation and other biological characteristics. At the same time, the geographical origin of seeds the influence of environmental factors during ripening, can also affect the dynamics of their germination. The most famous and widespread species of this genus is Moldavian snake head, it is widely cultivated as a melliferous, essential oil and ornamental plant (Adewinogo *et al.*, 2021). Multi-stemmed snake head and Hovering snake head (drooping snake head) are perennial plants used mainly in folk medicine (Melankina, Cicin, 2021). Also, it is generally known that specimens of the Moldavian snakehead species (K-7, K-8 and K-10 from the collection of the VIR) of physiology, differ in biochemistry, anatomical and morphological structure and therefore germinate in different ways. At the same time, specimens of the same species, from different geographical areas, can react to factors, *etc*. in different ways.

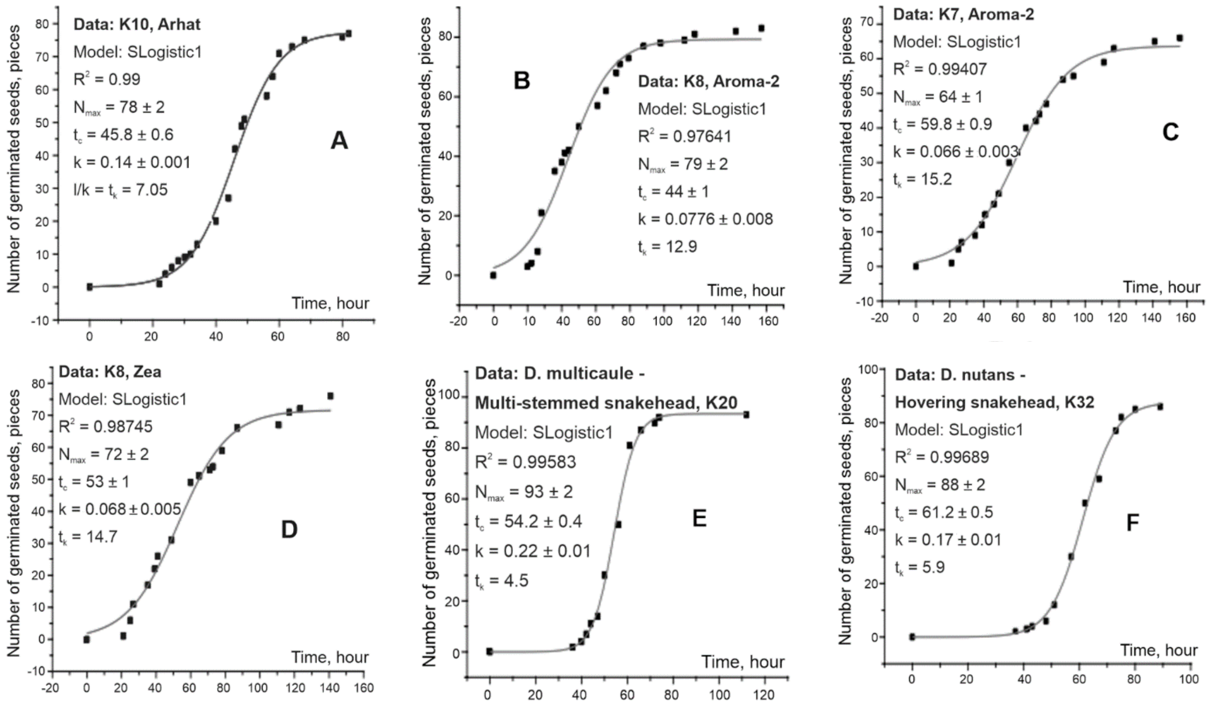

Figure 1. Dynamics of seed germination of snake head species
N – the number of germinated seeds during time *t*; N_{max} – the maximum number of germinated seeds; t_k – the rate of increase in the number of germinated seeds, is associated with a doubling of the number of germinated seeds and, therefore, reflects the rate of seed germination; t_c – the time at which the number of germinated seeds is equal to half of the maximum number of germinated seeds (which reflects the intensity of germination); with this: A – No. 1 *D. moldavica* L. – Moldavian snake head, variety Arhat, data: K 10; B – No. 2 *D. moldavica* L. – Moldavian snake head, variety Aroma-2, data: K 8: C – No. 3 *D. moldavica* L. – Moldavian snake head, variety Aroma-2, data: K 7; D – No. 4 *D. moldavica* L. – Moldavian snake head, variety Zea, data: K 8; E – No. 5 *D. moldavica* L. – Multi-stemmed snake head, data: K 20; F – No. 6 *D. nutans* – Hovering snake head, data: K 32.
where N – is the number of germinated seeds during time t; N_{max} – is the maximum number of germinated seeds; t_k – the rate of increase in the number of germinated seeds, is associated with a doubling of the number of germinated seeds and, therefore, reflects the rate of seed germination; t_c is the time at which the number of germinated seeds is equal to half of the maximum number of germinated seeds (which reflects the intensity of germination).

The structural features of the evaluated seeds include the following. A specialized fruit in *Dracocephalum* L. species – *coenobius* (*Coenobium* L.), when ripe, breaks down into 4 closed single-seeded fragments – erems (*Eremus* L.). (Fedorov, Artyushenko, 2016; Levina, 1987; Yakovlev *et al.*, 2018; Gubanov *et al.*, 2004). In this work, the terms erems and seeds are used interchangeably. The form of erems *Dracocephalum* L. is elongated-oval or elongated-obovate, flattened-trihedral with a convex wider dorsal edge and with flat and somewhat narrower ventral edges. Rafe (*Raphe* L.) in an oval or rounded depression of white colour. The surface of erems is smooth or slightly lumpy, brownish, gray or black in colour. Pericarp consists of 4 layers: exocarp, mechanical layer, parenchymal layer and endocarp. The seed coat grows together with the endocarp only in rafe (*Raphe* L.). It is single-layered of polygonal *Parenchymal* L. cells. Seeds with a straight formed embryo which consists of two cotyledons with pointed lower ends, a root with hypocotyl and a small bud. Endosperm in snake heads is represented by 1–3 rows of cells.

Considering that to describe the performance of any model, it is necessary to take into account the widest possible range of its capabilities and stability (Arseven, 2015), therefore, the species of *Dracocephalum* L. seeds are so heterogeneous in their features and were used to evaluate a dynamic seed germination model. As a result, we believe that since plant seeds are living organisms, it is necessary to describe their germination and the effect of action in dynamics. Thus, the dynamic model is realized which reflects the effect of germination due to the internal reserves of seeds, due to the activation of the endosperm.

Conclusions

The results of our research have shown that the mathematical model for an assessment of seed germination on the example of a genus *Dracocephalum L.* has been fully justified.

The dynamic model in the work reproduces changes in the initial phase of plant growth through the dynamics of seed germination has presented. That is, in this model there is a change in the state of a living object in "motion".

The model had a strictly formulation, which by the corresponding formulas was displayed. The dynamic model was significantly different from all previously used methods. For assessing the initial phases of plant growth based on static parameters.

In static models, the change in the state of plants was considered as objects that practically did not change over time. Since all the estimated indicators (germination, germination energy, *etc*.) were considered fixed in separate time sections were considered fixed.

The intensity of seed germination, which was assessed using a dynamic model, made it possible to select the most "active" seeds. This allowed active seeds to provide an exceptional opportunity for growing plants to take a leading position in the agrocenosis. Dominance in the agrocenosis allowed the plant to more actively obtain the main resources of the environment (moisture, nutrients, solar energy, *etc*.). Thus, this made it possible to ensure the highest productivity.

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Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Author contributions

AK 50%, NN 30%, EN 20% – study of the concept and design;
AK 50%, NN 40%, EN 10% − data collection;
AK 70%, NN 20%, EN 10% − analysis and interpretation of data;
AK 60%, NN 10%, EN 30% − writing a manuscript;
AK 40%, NN 10%, EN 50% − critical revision and approval of the final manuscript.

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