The rate equations and kinetic models of seed germination

Xueyong Zhou¹, a, Rongxia Fu¹, b*, Haiqing Wu¹,e, Jianzhong Xiao²,d, A.H. Rajasab³,e

¹Tianjin Engineering and Technology Research Center of Agricultural Products Processing, College of Food Science and Bioengineering, Tianjin Agriculture University, Tianjin300384, PR China;
²Tianjin Heima Industry and Trade Limited Company, Tianjin300384, PR China;
³Faculty of Science and Technology, Gulbarga University, Karnataka, Gulbarga 585308, India.

azhouxueyongts@163.com, bfurongxia@sina.com (*Corresponding author),
c362033920@qq.com, djiheima@163.com, eradjasab55@gmail.com

Abstract. The germination kinetic of seed can be used to judge the seed activity and provide experimental basis for the seeds breeding. However, the research of seed germination kinetics has been paid less attention. In the present study, the expression methods of seed germination rate and kinetics are summarized. The growth rate of seed can be expressed as fresh weight, dry weight, root length and bud length, respectively, and the rate equation has been provided in detail. The kinetic models of seed germination can be expressed by the first-order kinetic equation, Elovich equation, Langmuir equation and double constant equation. The meaning of parameters and the usage of models are discussed.

1. Introduction
Seed germination is the most intense period in the life of plants. During the seeds germination, a series of physiological and biochemical changes will occur. Some nutrients such as protein, starch and fat will be broken into small molecules, and the activity of amino acid, reducing sugars and some enzymes will increase.

The germination of seeds is usually divided into three stages[1-2]. The first stage is seed imbibition. After contacting with water, the seed is wetted and permeated by water. Strictly speaking, this state is a physical process but not physiological process, which will be over within 5h. The second stage is seed activity (5-26h). After water has been absorbed by seeds, the enzyme system of seeds starts to activate and the seeds respiration gradually increases, leading to the decomposition and transformation of storage materials in seeds. The insoluble starch, fats and protein transfer into soluble sugars, fatty acids and amino acids which can be utilized by embryos. During the decomposition and transformation of the above nutrients, the energy metabolism and thermogenesis will occur. At the later stage of seeds activation, the inflated seed coat limits the oxygen supplying. Simultaneously, the aerobic respiration of seeds changes into anaerobic respiration, leading to the stagnation of respiration and water absorption.

The third stage is seed germination (after 26 h). When the embryo cell expands to a certain extent, the seed radicle breaks through the seed coat, this process is called protrusion. After the seed
protrusion, the radicle and germ grow rapidly. During the seed germination, the metabolism and respiration of seed are extremely high. In the middle and later stages, the amount of nutrient substance decreases while the transport resistance of nutrient substance increases due to the sharp increase of cells number. The germ growth is gradually restricted, and the germination curve of seeds presents an S-type, i.e., in the initial stage, the germination rate of seeds is relatively stable, but in the middle stage, the germination rate of seeds increases rapidly. In the later stage, the germination rate of seeds becomes stable again[3].

Since seed germination is a dynamic process, the germination kinetic of seed can be used to judge the seed activity. Up to now, however, the research of seed germination kinetic has been paid less attention, and there are no unified models to describe the seed germination rate and kinetics. In the present study, the expression methods of seed germination rate and kinetics are summarized. The above summary can provide theoretical support to the kinetic research of seed germination.

2. Germination rate of seeds

The germination rate of seeds can be expressed by the increase of fresh weight (or dry weight) per unit time or the growth of bud length, which are introduced as follows.

2.1 Seed Growth rate of expressed as fresh weight

The growth rate of seed \( (r_{\text{fresh}}) \) can be expressed as the increase in fresh weight of seed per unit time:

\[
    r_{\text{fresh}} = \frac{dW_{\text{fresh}}}{dt}
\]

(1)

where: \( r_{\text{fresh}} \) is the growth rate of seed expressed as fresh weight, g/d; \( W_{\text{fresh}} \) is the fresh weight of seed at any time during germination, g; \( t \) is germination time of seed, d.

Since the germination of seeds requires water, the growth rate of seed expressed as fresh weigh is a comprehensive reflection of cell number and water content of seed, which has certain practical significance.

2.2 Seed growth rate expressed as dry weight

The growth rate of seed \( (W_{\text{dry}}) \) can be expressed as the increase in dry weight of seed per unit time[4]:

\[
    r_{\text{dry}} = \frac{dW_{\text{dry}}}{dt}
\]

(2)

where: \( r_{\text{dry}} \) is the seed growth rate expressed as dry weight, g/d; \( W_{\text{dry}} \) is the dry weight of seed at any time during germination, g; \( t \) is germination time of seed, d.

Seed dry weight can reflect the increase of seed biomass, therefore, it is more important than fresh weight in plant physiology research.

2.3 Seed growth rate expressed as root length

The development of seed begins with the radicle growth[5]. Firstly, the radicle needs to break through the seed coat, then the radicle starts to grow down. Therefore, the seed growth rate can be expressed as root length:

\[
    r_{\text{root}} = \frac{dL_{\text{root}}}{dt}
\]

(3)

where: \( r_{\text{root}} \) is the seed growth rate expressed as root length, cm/d; \( L_{\text{root}} \) is root length at any time during seed germination, cm; \( t \) is germination time of seeds, d.

2.4 Seed growth rate expressed as bud length

As the radicle grows, the germ also begins to grow, and then the cotyledon gradually starts to grow. The length of seed bud can reflect the characteristics of growth upward. The seed growth rate also can be expressed as the bud length:
\[ r_{\text{sprout}} = \frac{dL_{\text{sprout}}}{dt} \]  (4)

where: \( r_{\text{sprout}} \) is the seed growth rate expressed as bud length, cm/d; \( L_{\text{sprout}} \) is bud length at any time during seed germination, cm; \( t \) is germination time of seed, d.

3. Kinetic models of seed germination

The kinetic model reflects the relationship between seed growth and time\(^6\). If only the change of seed biomass is considered, the first-order kinetic equation, Elovich equation and double constant equation can be used. These equations are all non-structural models, i.e., they are empirical models. If the restrictive factors such as the amount of nutrients and their transportation resistance during seed germination are needed to consider, the germination kinetic needs to describe by the structural models.

3.1 Unstructured models for seed germination

3.1.1 The first-order kinetic equation

The first-order kinetic equation is one of the most commonly used equations to describe chemical reactions\(^7\), and its expression is:

\[ \ln Y = \ln Y_{\text{max}} + Bt \]  (5)

where: \( Y \) can be used as the fresh weight, dry weight, root length, bud length or other parameters of seed, respectively; \( Y_{\text{max}} \) is the maximum value of the above parameters; \( B \) is a constant, and \( T \) is the germination time. The straight line can be obtained by plotting \( \ln Y \) versus \( t \), and the fitness of the model can be determined according to the linear parameter.

3.1.2 Elovich equation

Elovich equation is widely used for the kinetics of soil adsorption\(^8\), and its simplified form is:

\[ Q = A + B \ln t \]  (6)

where \( Q \) is the adsorption amount, \( A \) and \( B \) are constants, and \( t \) is the adsorption time.

Elovich equation can also be used to describe the kinetic of seed germination. In equation (5), \( Q \) can be used as fresh weight, dry weight, root length, bud length or other parameters of seed, respectively. A straight line can be obtained by plotting \( Q \) against germination time \( t \), and the fitness of the model can be judged according to the correlation coefficient of the straight line.

3.1.3 Double-constants equation

The double-constants equation is the empirical equation. It is suitable to describe the kinetic characteristics in the complex reaction process. Its equation is given as follows\(^9\):

\[ \ln Y = A + B \ln t \]  (7)

where: \( Y \) can be used as the fresh weight, dry weight, root length, bud length or other parameters of the seed, respectively; \( A \) and \( B \) are constants, and \( t \) is the germination time of the seed. A straight line can be obtained by plotting \( \ln Y \) to \( \ln t \), and the fitness of the model can be judged according to the correlation coefficient of the straight line.

3.1.4 Langmuir kinetic equation

Langmuir kinetic equation is also used to describe the kinetic change of seed biomass\(^10\), and its expression is as follows:

\[ \frac{t}{Y} = \frac{t}{Y_{\text{max}}} + \frac{1}{K} \]  (8)

where: \( Y \) can be used as the fresh weight, dry weight, root length, bud length or other parameters of the seed, respectively; \( Y_{\text{max}} \) is the maximum value of the above parameters; \( K \) is the equilibrium constant, and \( t \) is the germination time. A straight line can be obtained by plotting \( \ln t/Y \) to \( t \), and the fitness of
the model is determined according to the correlation coefficient of the straight line.

4. Conclusions
Based on the analyses of growth characteristics of seed, the rate equations of seed germination growth were provided. The growth rate of seed can be expressed as fresh weight, dry weight, root length and bud length, respectively. The kinetic models of seed germination can be expressed by the first-order kinetic equation, Elovich equation, Langmuir equation and double constant equation. The above results can provide reference for the kinetic research of seed germination.

Acknowledgements
The research was funded by the Tianjin Key Projects of Scientific and Technological Support (18YFZCNC01270 and 17YFZCNC00220).

References
[1] J. L. Wang, F.C. Guan. Advanced crop physiology. China Agricultural University Press, Beijing, 2013.
[2] Y. C. Hu. A study of the thermogram and the thermo-kinetics of the germination of Robinia pseudoacacia seeds. Journal of Central-South Forestry College, 1995, 15(1): 20-23.
[3] Z. Liu. Spermology. Chemical Industry Press, Beijing, 2015.
[4] J. H. M. Thornley. Mathematical Models in Plant Physiology. Academic Press, London, 1976.
[5] D. Chen, T. Wang. A mathematical model for the response of primary root elongation to environment. Acta Phytophysiologica Sinica, 1989, 15(4): 365-370.
[6] W. Li, X. L. Zhang, U. Ashraf, et al. Germination, seedling growth and physiological responses of sweet corn PEG-induced water stress. Pakistan Journal of Botany, 2017, 49(2): 639-646.
[7] D. Xu, X. Li, Y. Wang, et al. Washing kinetics characteristics of Pb and Cd from contaminated soil with FeCl₃-citric acid. Chinese Journal of Environmental Engineering, 2016, 10(11): 6753-6760.
[8] Z. Zhang, Z. Meng, Y. Zhang. Reconsideration about Elovich equation. Chinese Journal of Soil Science, 2000, 31(5): 208-209.
[9] D. Zhu, S. Zou, C. Zhou, et al. Cd²⁺ adsorption characteristics of typical soils in karst areas. Carlsologica Sinica, 2015, 34(4): 402-409.
[10] G. Guo, Q. Zhou. Adsorption behavior of cadmium in phaeozem and burozem. Chinese Journal of Applied Ecology, 2005, 16(12): 2405-2408.