ISSN: 0023-074X
Volume 69, Issue 01, January, 2024

The definition of the potential energy of deformation in the elastic rods of the working elements of devices for shaking off Colorado beetles

Arendarenko V.[1], Semenov A.[1], Kharak R.[1], Antones A.[1], Opara N.[1], Skrypnyk V.[1], Yeleussinov B.[2], Sakhno T.[3]

Department of Engineering and Technology, Poltava State Agrarian University, Poltava, Ukraine[1]
Branch of JSC «NCPD Orleu», Institute of professional development in Kzylorda region, Kazakhstan[2]
Department of Biotechnology and Chemistry, Poltava State Agrarian University, Poltava, Ukraine[3]

Keywords:
Colorado potato beetle, harvesting device, elastic rods, polymeric materials, potential energy

ABSTRACT

The aim of the study is to develop and determine the effectiveness of a device for shaking off the Colorado potato beetle (Leptinotarsa decemlineata Say) and its larvae from potato bushes. Theoretical studies include the analysis of the effect of transverse force on the potential strain energy of various types of elastic rods: nylon, fibreglass, organoplastic and carbon fibre. Experimental studies were carried out using elastic rods of circular shape with a diameter of 10 mm and different lengths of 200, 250 and 300 mm. The influence of the ratio of elastic moduli and the ratio of length to diameter on the potential strain energy was determined. The results of the study show that for the effective use of round elastic rods with a low ratio η (length to diameter), it is advisable to use materials with a low value of γ (ratio of elastic moduli). The nylon material corresponds to this value. In the case of large values of η, it is more expedient to use composite materials, as this maintains a high potential strain energy. It has also been found that the angle of maximum deflection of the rods affects the value of the potential strain energy and depends on the parameters of the rods and the size of the potato bush. The developed device with elastic rods allows to effectively use the mechanical method to control the Colorado potato beetle and its larvae on potato bushes.

1. INTRODUCTION

Ukraine's economic growth is directly linked to the widespread use of modern resource-saving and environmentally friendly technologies in agriculture to produce competitive products. Due to its natural climatic conditions, the country is a major producer and consumer of potatoes [1]. According to the Food and Agriculture Organization of the United Nations (FAO STAT) [2], it is one of the most important food crops after wheat, corn, and rice. This crop plays an increasingly important role in the future global food security [3]. Potatoes are grown on almost all continents of the world and are a significant agricultural sector in many countries [4]. China and India are the world's largest potato producers, accounting for 25% and 14% of total world production, respectively [5]. It is known that in 2023, 21 million tons of potatoes were harvested in Ukraine [5]. Ukraine is one of the five largest potato producers in the world (5% of global production). At the same time, domestic demand for this crop does not exceed 5 million tons. According to statistics, the average potato yield on farms and private households is 37.0-45.0 t/ha, and for special purpose production it is no more than 30 t/ha [6].

In all countries where potatoes are grown, it is necessary to provide for the mandatory protection of potato plantations from diseases and pests [7]. The Colorado potato beetle is a malicious pest [3], [8], which belongs to the family of leaf beetles Chrysomelidae, genus Leptinotarsa. The harmfulness of the Colorado potato beetle on potatoes is not only reduced in yield but also in tuber size and nutrients [9]. The quantitative losses of potatoes due to insect pests are 34% annually [10]. Among the existing methods of protecting potato plantations from the Colorado potato beetle, the chemical method is currently the main one [9]. It is reliable, has a rapid effect on pests, and is not dependent on meteorological factors and the state of pest populations. At the same time, prolonged use of chemicals leads to a decrease in their effectiveness due to the emergence of resistant populations of the beetle and its resistance and adaptation to insecticides [11], [12]. The paper [13] provides recommendations for insecticide rotation during the growing season. In addition, pesticides accumulate during the cultivation of potato plantations [14]. Pesticide residues that remain in food materials have a harmful effect on human health and the environment, including soil, water and air pollution [15]. Due to which ultraviolet radiation is used in the pre-sowing treatment of agricultural crops to reduce the use of chemically dangerous growth stimulants [16], [17]. Therefore, science is faced with the task of finding environmentally friendly ways and means of protecting potato plantations from the Colorado potato beetle.

The biological method is used to produce ecological potatoes [18]. It does not disturb the ecological balance in the soil and on plants, does not pollute the environment with toxic substances, and does not have a harmful effect on humans. Biological methods also include the activation of the local beneficial entomofauna of the potato field with the use of specialized entomopathogenic fungi [9] and entomopathogenic nematodes [19]. The article [20] discusses the effect of acoustic waves on living organisms. In laboratory conditions, the effect of acoustic fields on plant pests with a frequency corresponding to the resonance frequency of the pests' bodies was studied. The acoustic field causes a destructive effect, in which the Colorado potato beetle dies under the influence of acoustic vibrations. Experiments on the destruction of the Colorado potato beetle using the acoustic method depend on a number of factors and the resonant state of insects. Therefore, this area requires more in-depth research.

An alternative to chemical, biological and acoustic methods of controlling the Colorado potato beetle are mechanical methods with various types of devices [21], [22]. Such methods allow small farms to obtain environmentally friendly products without the use of pesticides. Paper [21] presents a pneumatic method of collecting pests in special containers by blowing plants with a pulsating air flow on both sides. The Colorado potato beetle was collected at air flow rates of 35 and 45 m/s. It was found that the most complete collection of the beetle occurs at an air flow rate of 45 m/s. The disadvantage of this technical solution is that the pulsating air flow raises lumps of soil and dust into the suction system of the device. A similar pneumatic device was considered in [22], where the results of tests of the pneumatic device in the field were presented using three air flow rates, respectively 31, 35, 38 m/s and two tractor unit speeds (5 and 6 km/h). The results showed that the airflow rate and the tractor speed did not have a significant effect on the CPB displacement ($p = 0.0548$ and 0.7033, respectively). The most effective airflow velocity that resulted in the removal of most CPB larvae from potato leaves was 35 m/s. Large-scale tests of the developed device were not conducted. In [23], scientists propose a system for collecting the Colorado potato beetle based on the principle of vacuum collection. These devices consist of a vacuum chamber that is connected to the suction nozzle of a fan. The principle of suction by air flow into the nozzles and collection of pests in special tanks is used. The influence of various combinations of air flow velocities, air flow widths, and movement speeds was studied. The effectiveness of this system in comparison with traditional approaches is evaluated. In [24], the authors propose to use a diffusion device to collect harmful insects. It consists of a chamber with a horizontal slit in the lower part of the chamber. Through this slit, pests are sucked in due to the low vacuum created by a centrifugal fan. The pests are transported to the collection container by a strong air flow. The disadvantage of this device is the inability to collect pests from the inner stems of potatoes. There are other designs of devices based on the principle of suction, for example, two-chamber and combined [25], which significantly complicate the design. The analysis confirms the effectiveness of the mechanical method of harvesting the Colorado potato beetle in potato cultivation. Mechanical methods use different configurations of working bodies [26]. Thus, work [26] describes the work of passive working bodies (PWBs). Passive working bodies shake off pests by repeatedly hitting the potato bushes with elastic rods due to the translational movement of the tractor unit. The elastic rods can be made of different elastic materials, different lengths, diameters and shapes. The analysis of pneumatic and mechanical methods with active working bodies of devices for collecting and destroying the Colorado potato beetle indicates that mechanical devices are structurally simpler than pneumatic ones. They can be used effectively in small potato fields. For mass use, it is necessary to carry out scientifically based calculations of the effective use of elastic rods made of different polymeric materials.

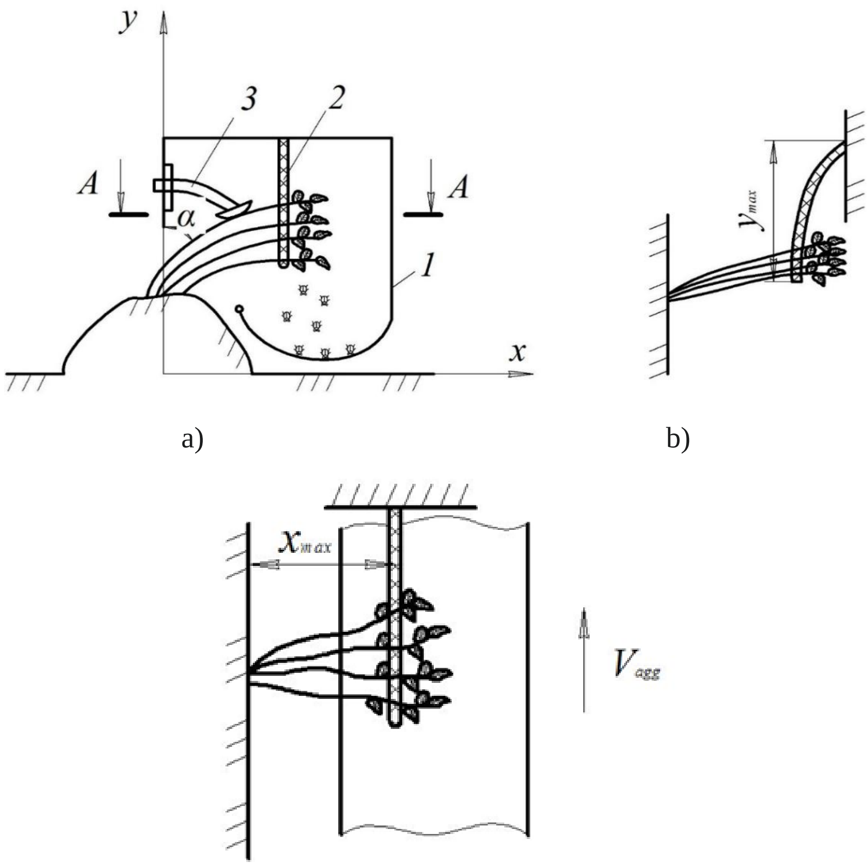
The aim of this work is to theoretically study the potential energy of rods made of different elastic materials for passive working bodies in Colorado potato beetle harvesting devices. To achieve this goal, we need to solve the following tasks: to develop a scheme of a device with passive-type working bodies made of different elastic materials; to theoretically investigate the effect of the transverse force on the potential strain energy depending on the dimensional parameters of the rods.

2. Research materials and methods

Passive elastic rods are used in machines for collecting and destroying the Colorado potato beetle [26]. The materials used for these rods were nylon, fibreglass, carbon fibre and organoplastic. The choice of a particular material was made based on its characteristics and suitability for use in the control of the Colorado potato beetle. The dimensions of the elastic rods were selected individually depending on the size of the potato bushes. Hooke's law was used to determine the potential elastic deformation energy of elastic rods [27]. The calculation of this energy allows us to estimate the extent to which the rods can be deformed under the action of an external force. To analyses the deformation in the rods and determine the potential energy as a function of the transverse force, the analytical method described in [28], [29] was used. This method made it possible to systematically study the effect of transverse force on elastic rods and their potential energy. The application of these theoretical studies made it possible to determine the optimal parameters of elastic rods for the most efficient use in machines for controlling the Colorado potato beetle on potato bushes.

3. Research results

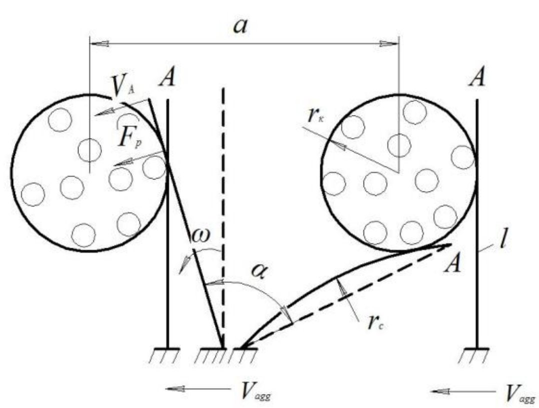
To carry out theoretical studies of the interaction of elastic rods, a schematic diagram for collecting pests from potato plantations was proposed (Fig. 1). It consists of a U-shaped chamber 1 in the middle of which there are elastic rods 2. On the inner side surface of chamber 1, a device 3 is installed to bend the stems of potato bushes towards the tray. During the forward movement of the device along the potato plantations at a speed of Vagg, the stems of the potato bushes are bent towards the horizon. As a result, the elastic rods begin to interact with the stems and leaves of the potato. The created shock-oscillatory effect shakes the Colorado potato beetle into the tray of the device.



c) (A-A)

Figure 1. A device for collecting Colorado potato beetles: a - front view; b - top view; c - side view.

On the Fig. 2 shows the scheme of interaction of the elastic working body (EWB) with the stem of a potato bush.



a) b)

Figure 2. Scheme of interaction of an elastic rod with the stem of a potato bush: a - interaction of an elastic rod with the stem; b - impact of an elastic rod on the stem (*a* - distance between potato bushes).

The following assumptions were made when performing theoretical studies of the device's motion:
- the bush is schematically represented as a circle with a radius of r_k;
- pests are evenly distributed over the volume of the potato bush;
- the pest control device moves at a constant speed equal to the speed of the tractor unit $V_{агр}$;
- the angular velocity ω of an elastic rod depends on the material from which it is made.

When the elastic rod comes into contact with the stems of the potato bush, it deflects (Fig. 2, a). As the rod moves along the stems of the bush, the shock and oscillation effect shakes the pests to the bottom of the tray. After the rod leaves the contact with the stems of the bush, it bends and hits the stems of the next bush (Fig. 2, b). Let us consider the deformation of a round-shaped RO when it interacts with the stems of a potato bush. We will assume that there is no friction between the stems and the crown of the bush when interacting with the RO. Under the action of the device that bends the stems of potato bushes, they deviate by the value $\boldsymbol{x_{max}}$, while the elastic rods bend by the value $\boldsymbol{y_{max}}$ (Fig. 1). Determine the maximum angle of deviation of the elastic rod from the established equilibrium at the moment it leaves the contact zone with the stems of the bush. The calculation scheme of this process is shown in Fig. 3. The boundary conditions of this deformation problem are as follows: $BD = l - r_k \cdot (1 + \sin\alpha)$; $AD = a - r_k(1 + \cos\alpha)$; $y_{\max}$ = const, where l – is the length of the elastic rod; r_k is the average radius of the potato bush; α is the angle at which the elastic rod leaves contact with the bush stems; y_{max} is the maximum deflection of the rod.

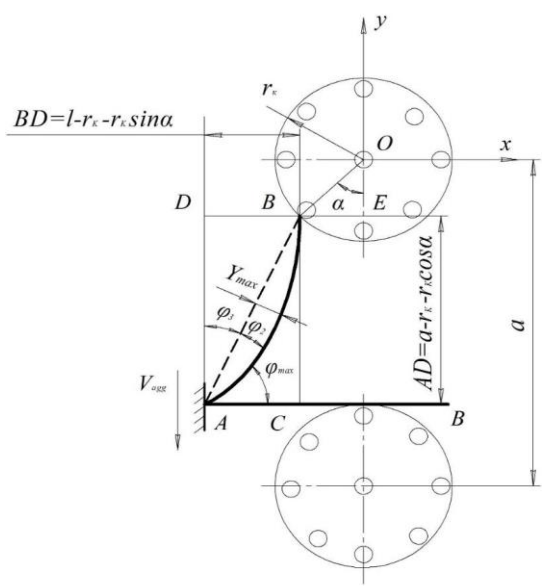


Figure 3. Diagram for determining the maximum angle of deflection of an elastic rod without damaging the stems of a potato bush.

From the triangle ADB, determine the angle φ_3:

$$\varphi_3 = \tan^{-1}\left(\frac{l/r_к - 1 - \sin\alpha}{l/r_к - 1 - \cos\alpha}\right) \quad (1)$$

By entering the designation $\delta = \frac{l}{r_k}$ i $\Delta = \frac{a}{r_k}$, formula (1) will take the following form:

$$\varphi_3 = \tan^{-1}\left(\frac{\delta - 1 - \sin\alpha}{\Delta - 1 - \cos\alpha}\right) \quad (2)$$

From the triangle ADB, determine the length of the hypotenuse AB:

$$AB = \sqrt{(l - r_k(1 + sin\, sin\, \alpha\,))^2 + (a - r_k(1 + cos\, cos\, \alpha\,))^2} \quad (3)$$

The angle φ_2 is found through the maximum deflection of the elastic rod:

$$\varphi_2 = \tan^{-1}\frac{y_{max}}{AB}\ (4) \quad (4)$$

The maximum deflection angle of the elastic rod, taking into account expressions (2) and (4), is:

$$\varphi_{max} = \frac{\pi}{2} - \left[\tan^{-1}\frac{\delta - 1 - \sin\alpha}{\Delta - 1 - \cos\alpha} + \tan^{-1}\frac{y_{max}}{AB}\right] \quad (5)$$

The elastic rod, bent at an angle of φ_{max}, receives a certain potential energy, which is necessary to strike the next stem. As a result of this impact, the colorful beetles are shaken into the tray of the device. The work of external forces (*A*) is equal in magnitude to the potential energy of elastic deformation of an elastic rod interacting with the stems of potato bushes. Let's write the deformation energy of an elastic rod under the action of a bending moment and a transverse force.

$$U = A = U_1 + U_2, \quad (6)$$

where U_1, U_2 – are, respectively, the potential energy from the bending moment and the transverse force.
The potential energy from the bending moment is determined by the following formula:

$$U_1 = U_1 = \int_0^l \frac{M^2(x)dx}{2EI} = \frac{M^2(x)dx}{2EI} = \frac{F^2 l^3}{6EI}, \quad (7)$$

where EI - stiffness of the elastic rod in tension (compression), Н·м^2; M – bending moment, Н·м; F – elasticity of the elastic rod, Н; l – rod length, м, E – modulus of elasticity of the rod, I – moment of inertia of the cross-section of the elastic rod.
Expression 7 expresses the deformation due to the bending moment as the rod curvature increases (fig.1, c).
The potential energy arising from the transverse force Q can be defined as follows.

$$U_2 = k\int_0^l \frac{Q^2(x)dx}{2GS} = \frac{kF^2 l}{2GS} \quad (8)$$

where k – is a coefficient that depends on the shape of the rod and characterises the uneven distribution of tangential stresses across the cross-section of the rod (k =1,2 for rods of rectangular cross-section, k = 32/27 for a circular cross-section), GS is the stiffness of the rod under shear, H·m^2
Substituting U_1 and U_2 into (1), we obtain

$$U = \frac{F^2 l^3}{2EI} + \frac{kF^2 l^3}{2GS} = \frac{F^2 l}{2}\left(\frac{l}{3EI} + \frac{k}{GS}\right). \quad (9)$$

Assuming the shape of an elastic rod in the form of a cylinder of length l and diameter d, and considering that for this case the parameters have the following values:

$$I = \frac{\pi d^4}{64}, \quad S = \frac{\pi d^2}{4}$$

substituting these values into (4), we obtain:

ISSN: 0023-074X
Volume 69, Issue 01, January, 2024

$$U = \frac{4F^2l}{\pi d^2}\left(\frac{8l^2}{3Ed^2} + \frac{k}{2G}\right) \tag{10}$$

Let's estimate the value of U_2 compared to U_1. To do this, let us represent (10) as follows:

$$U = \frac{32F^2l^4}{3Ed^2}(1 + z(\eta;\gamma)) \tag{11}$$

$$z(\eta;\gamma) = \frac{3k\gamma}{8\eta^2}, \tag{12}$$

where $\gamma = \frac{E}{G}$ – ratio of elastic moduli of an elastic rod; $\eta = \frac{l}{d}$ – the ratio of the length of the elastic rod to its diameter.

Relationship (12) expresses the degree of influence of the transverse force on the potential energy of an elastic rod. For clarity, it is advisable to express these values as a percentage. The contact of the elastic rod with the stems of the first bush in the row begins at point A and ends at point B. The rod bends to form an arc with a radius of r_c. As it moves along the stems of the bush, the elastic rod is constantly bent and unbent, producing an oscillatory effect. Based on the contact interaction with the stems of the first bush, the maximally deformed rod strikes the stems of the second bush with a force Fp. The impact can be in the center of the bush or from the side. A central impact will occur when the length of the elastic rod l is equal to the distance between the potato bushes in row a. In case of a lateral impact, the distance between the potato bushes in the row may be greater than the length of the elastic rod or less (Fig. 3). Accordingly, the impact force will be different, and the shaking of pests is reduced.

In the field, studies were conducted on the effect of transverse force on the potential energy of an elastic rod. Elastic rods of circular shape with a diameter of 10 mm, length of 200, 250 and 300 mm made of nylon (E = 400...2000 MPa, G = 450...480 MPa), fibreglass (E=18000...22000 MPa, G = 450...480 MPa) and composite materials, respectively, were used in the experiments. For these materials, an indicator was determined γ. Thus, for rods made of nylon, this indicator ranged from 3.1 to 4.2 (приймався $\gamma_{\text{сер}} = 3{,}5$), for fibreglass – γ = 5,14...5, 5 (accepted $\gamma_{\text{сер}} = 5{,}25$), polystyrene – γ = 40, carbon fibre – γ = 100. The degree of influence of the transverse force on the potential strain energy, depending on the dimensional parameters of elastic rods, is given in Table 1.

Table 1. Degree of influence of the transverse force on the potential strain energy depending on the dimensional parameters of rods made of different elastic materials.

$\eta = \frac{l}{d}$	Meaning Z, %			
	Material of the rods			
	Nylon	Fibreglass	Organoplastics	Carbon fibre
5	6,2	20,1	71	177
10	1,6	5,4	17,8	48,6
15	0,7	2,4	7,9	20,0
20	0,4	1,3	4,4	11,2
25	-	-	2,9	7,1
30	-	-	0,7	5,0

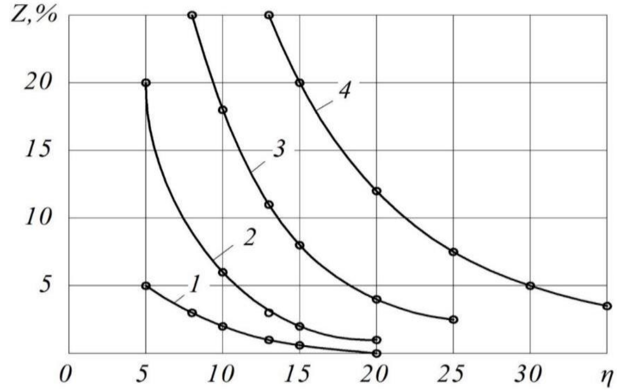


Fig. 4. Diagram of the influence of the transverse force on the potential strain energy depending on the dimensional parameters of rods made of different materials: 1 - nylon; 2 - fibreglass; 3 - organoplastic; 4 - carbon fibre.

The elastic rods are mounted on textolite plates, which vary depending on the rod material. Based on the results obtained, a graph of the dependence of $Z = f(\eta)$. After analysing the graph, we conclude that for modern elastic materials, the effect of a transverse force on the potential energy of a rod depends on the ratio of the rod's elastic moduli.

4. Discussion

The research addresses an important problem in agriculture - the control of crop pests (potatoes). The analysis of mechanical methods of collecting Colorado potato beetles showed that pneumatic devices have certain disadvantages. For example, in [21], the use of a pneumatic device at a speed of 45 m/s provided only 44% collection efficiency, which dropped to 21,2% when the speed was reduced to 35 m/s. Such results do not meet the requirements for effective collection of Colorado potato beetles and are not economically viable for reuse. In another study [22], the authors opted for an air flow rate of 35 m/s, with a mechanical transport unit speed of 5 to 6 km/h. However, this pneumatic device requires large-scale testing to determine its effectiveness in collecting pests and determining the number of damaged plants. In [23], a pneumatic system was used, but the speed of the machine did not exceed 6.0 km/h, and although the damage coefficient of the leaf mass was small, the damage by the tractor wheels was serious. Pneumatic devices, in general, have important disadvantages such as complexity, high power consumption and limited performance, which does not ensure effective pest collection [24]. However, these disadvantages can be eliminated by switching to a device with passive working bodies. This will allow achieving mechanical shaking of Colorado potato beetles from plants at optimal productivity and efficiency, avoiding the problems associated with pneumatic systems. Passive working bodies that interact with potato stems can effectively reduce pest populations by using the oscillatory effect. Theoretical studies have shown that the efficiency of the system significantly depends on the dimensional parameters of elastic rods and their materials. For different materials, such as nylon, fibreglass, organoplastics and carbon fibre, the established values of the degree of influence of the transverse force on the potential strain energy vary with respect to the rod dimensions. This indicates the need for careful selection of material and parameters to achieve the optimum pest control effect. The analysis of Table 1 and Figure 4 shows that the optimal rod length depends on its ratio to the distance between plant rows. This may indicate the need for an individual approach when choosing the length of the rod, depending on the vegetative state of the plants and economic conditions. The analysis of the graph of efficiency versus the ratio of elastic moduli of different materials shows that modern elastic materials exhibit optimal efficiency at certain ratios of elastic moduli. This is important to consider when choosing a material for the manufacture of elastic rods. The transverse force plays a key role in the interaction of the system. Looking at Table 1, it is possible to determine the optimum values of the transverse force for different rod sizes and materials. This can be an important factor in the design and improvement of such systems.

5. Conclusion

When using round elastic rods with a $\eta \leq 20$ in devices for shaking and killing the Colorado potato beetle in potato fields, a material with a low γ value should be selected. This value corresponds to nylon. If $\eta \geq 20$, it is more advisable to use composite materials. The potential deformation energy of the rods is affected by the angle of their maximum deflection, which in turn depends on the length and diameter of the rod, the material of the rod and the size of the potato bush. Therefore, at constant values of η=const, the error in calculating the potential energy without taking into account the influence of the transverse force in the working body increases with an increase in the γ. For modern materials from which elastic rods are made, at $\eta \geq 20$, the error in calculating the potential energy without taking into account the effect of the transverse force does not exceed 5% and can be neglected.

6. References

[1] Wijesinha-Bettoni R, Mouillé B. The contribution of potatoes to global food security, nutrition and healthy diets. American Journal of Potato Research, 2019, 96: 139 -149

[2] Food and Agriculture Organization of the United Nations FAOSTAT [(accessed on 23 December 2023)], Available at: https://www.fao.org/faostat/en/#home (Jan18, 2024)

[3] Kadoić Balaško M, Mikac K M, Bažok R, Lemic D. Modern Techniques in Colorado Potato Beetle (Leptinotarsa decemlineata Say) Control and Resistance Management: History Review and Future Perspectives. Insects, 2020, 11: 581

[4] Çalişkan M E, Bakhsh A, Jabran K. (Eds.). Potato Production Worldwide. London: Academic Press, 2022, 490

[5] Potato News Today. Global potato statistics: Latest FAO data published., 2023. Available at: https://www.potatonewstoday.com/2023/01/21/global-potato-statistics-latest-fao-data-published (Jan23, 2024)

[6] Agroberichten Buitenland. Large Scale Potato Growing in Ukraine., 2021. Available at: https://www.agroberichtenbuitenland.nl/documenten/publicaties/2021/12/28/large-scale-potato-growing-in-ukraine (Jan23, 2024)

[7] Alyokhin A, Rondon S I, Gao Y. (Eds.). Insect Pests of Potato: global Perspectives on Biology and Management. San Diego: Academic Press., 2022, 518

[8] Radcliffe E B, Lagnaoui A. Pests and Diseases. In Potato Biology and Biotechnology: Advances and Perspectives, 1st ed.; Vreugdenhil D, Bradshaw J, Gebhardt C, Govers F, Taylor M A, MacKerron D K, Ross H A, Eds. Elsevier: Oxford, UK, 2007: 545 -554

[9] Ropek D, Kołodziejczyk M. Efficacy of Selected Insecticides and Natural Preparations Against Leptinotarsa decemlineata. Potato Res, 2019, 62: 85 -95

[10] Oerke E C. Crop losses to pests. J. Agric. Sci., 2006, 144: 31 -43

[11] Alyokhin A, Mota-Sanchez D., Baker M., et al. The Red Queen in a potato field: integrated pest management versus chemical dependency in Colorado potato beetle control. Pest Management Science, 2015, 71: 343 -356

[12] Pélissié B, Chen Y H., Cohen Z P, et al. Genome Resequencing Reveals Rapid, Repeated Evolution in the Colorado Potato Beetle. Molecular Biology and Evolution, 2022, 39, 2: msac016

[13] Huseth A S, Groves R L, Chapman S A, et al. Managing Colorado potato beetle insecticide resistance: New tools and strategies for the next decade of pest control in potato. Journal of Integrated Pest Management, 2014, 5, 4: A1 -A8

[14] Bajwa U, Sandhu K S. Effect of handling and processing on pesticide residues in food - a review. J Food Sci Technol, 2014, 51, 2: 201 -220

[15] Khelifi M, Laguë C, de Ladurantaye Y. Physical Control of Colorado Potato Beetle: A Review. Applied Engineering in Agriculture, 2007, 23, 5: 557 -569

[16] Semenov A, Sakhno T, Hordieieva O, Sakhno Y. Pre-sowing treatment of vetch hairy seeds, Vicia Villosa using ultraviolet irradiation. Global Journal of Environmental Science and Management, 2021, 7, 4: 555 -564

[17] Semenov A, Korotkova I, Sakhno T, et al. Effect of UV-C radiation on basic indices of growth process of winter wheat (Triticum Aestivum L.) seeds in pre-sowing treatment. Acta Agriculturae Slovenica, 2021, 116, 1: 49 -58

[18] Cingel A, Savić J, Lazarević J., et al. Extraordinary adaptive plasticity of Colorado potato beetle: "Ten-striped Spearman" in the era of biotechnological warfare. International Journal of Molecular Sciences, 2016, 17, 9: 1538

[19] Askar A G, Yüksel E, Bozbuğa R, et al. Evaluation of Entomopathogenic Nematodes against Common Wireworm Species in Potato Cultivation. Pathogens, 2023, 12: 288

[20] Sokol G I. Acoustic Method of Colorado Beetle Elimination and It's Realization, 2015. European Journal of Biophysics, 2015, 3, 5: 38

[21] Reshadsedghi A, Taheri M R Y. Design, construction and evaluation of a portable machine for pneumatic collecting of Colorado beetle in potato fields. Agricultural Engineering Research Institute (Iran), 2009, 10, 3, 69 -82

[22] Almady S, Khelifi M. Design and Preliminary Testing of a Pneumatic Prototype Machine to Control the Colorado Potato Beetle. Applied Engineering in Agriculture, 2021, 37, 4: 645 -651

[23] Lacasse B, Lague C, Khelifi M, Roy P-M. Effects of airflow velocity and travel speed 0 'the removal of Colorado potato beetles from potato plants, Can Agric Eng, 1998, 40: 265 -272

[24] Vincent C, Boiteau G. Pneumatic Control of Agricultural Insect Pests. In: Vincent C., Panneton B., Fleurat-Lessard F (eds). Physical Control Methods in Plant Protection. Springer, Berlin, Heidelberg, 2001:

270 -281

[25] Rifai M N, Lacko-Bartosova M, Minar M. Effectiveness of Bio-Collector in Control of the Colorado Potato Beetle. Machinery and Technology for Sustainable Agriculture. Narodna Pobocka Istro na Slovensku, 1998, 4 -6

[26] Arendarenko V, Kharak R, Samoylenko T. Analysis of device for collect and dispose of Colorado beetle. The bulletin of the Petro Vasilenko Kharkiv national technical university of agriculture, 2011, 107: 203 -207.

[27] Garrett S L. Elasticity of Solids. In: Understanding Acoustics. Graduate Texts in Physics. Springer, Cham., 2020: 179 -23.

[28] Kudinov I V, Kudinov V A, Eremin A V., Zhukov V V. Mathematical model of rod oscillations with account of material relaxation behaviour. IOP Conf. Series: Materials Science and Engineering, 2018, 327: 042059

[29] Serazutdinov M N. Statics and dynamics of curved rods based on Bernoulli hypotheses and relations for a rectilinear rod. Structural Mechanics of Engineering Constructions and Buildings, 2023, 19, 1: 73 -83