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Justification of the Parameters of the Soil Preparation Module of the Potato Planting Machine

This work presents a substantiation of the parameters of the soil preparation module in a potato planting machine system, which is used for strip milling and primary covering of potato seeds. The proposed methodology allows describing the geometric and kinematic parameters of the milling drum blade, whose knife is formed by several sections, determining initial conditions and modeling the flight trajectories of soil chips. It also covers their interaction with the guiding casing surface, considering either reflection or sliding of soil particles into the target zone for primary covering of potato seeds. Based on the conducted analysis, an analytical expression for the shape of the casing is proposed, which, when interacting with soil chips, meets the requirement of directing soil particles into the target seed row zone.
potato seed, soil chips, planting, strip milling, parameters, modeling, analysis, guiding casing, flight trajectory, grinding, loosening

Problem statement. Potato production in Ukraine is largely concentrated in small private farms. This indicates a significant need for the development of effective small-scale mechanization tools. In most cases, the technological process of potato production remains poorly mechanized. For example, the issues of soil preparation for forming a seedbed for potato planting, as well as the mechanized planting process itself, are still underdeveloped. The low level of resource provision in such farms often leads to violations of proper crop cultivation technologies. As a result, potato yields in these farms are significantly lower compared to those of larger producers, where production technologies and resource availability are at a higher level. Therefore, one of the priority tasks of agricultural machinery development is the development of our own line of machines for potato production specifically tailored to these small-scale farms, which ensure the majority of Ukraine's gross potato collection.

The aim of this study is to justify the parameters of individual units of a combined potato planting machine. This research focuses on the study of the design and kinematic parameters of the milling module of the potato planter. This module, performing strip milling, is intended to prepare the soil for forming the potato seedbed and to initially cover the planted seed with loosened soil discharged from under the milling cutter's knife.

Analysis of recent research and publications. At present, many researchers tend to agree and confirm that strip milling during potato planting is a promising method of soil preparation. Specifically, strip milling of the row zone to the depth of potato planting promotes the formation of an appropriate clod structure, enabling the coulter to create an optimal planting bed and thus improving the conditions for plant development. Moreover, this approach allows for significant energy savings during milling, as only the furrow formation zone is cultivated [2, 4, 5, 9, 11].

In studies [1, 3, 6–8], the authors demonstrate the agrotechnical efficiency of high-quality soil preparation, particularly strip milling, prior to potato planting and compare the results with traditional soil preparation methods. The obtained results have a direct positive impact on increasing potato yield. Other studies [10, 12, 13] indicate that a combined potato planting machine, which integrates soil preparation with simultaneous planting and fertilization, is effective. This approach significantly reduces the number of field passes and ensures optimal planting conditions.

In works [3] and [4], the interaction of working bodies with both the soil and the potato seeds is elaborated, with constructive and kinematic parameters substantiated. These studies emphasize the high effectiveness of milling for subsequent furrow formation. However, issues related to modeling the trajectory of soil chip movement, its interaction with the guiding casing, and the initial covering of potato seeds with soil remain insufficiently developed.

The analysis of the literature confirms that these issues are highly relevant and require scientific solution.

Statement of the task. The aim of the study is to justify constructive and kinematic parameters of the milling module of the potato planting machine in order to ensure its functions of soil loosening and grinding, along with the primary covering of potato seed in the opened furrow.

Presentation of the main material. The use of strip milling in the potato planting unit is intended to grind and loosen the surface soil layer to the depth of seed placement. Moreover, the quality of planting depends on the type of soil that covers the seed. Therefore, the idea behind combining working elements in the potato planting unit is to ensure that the soil chips initially partially cover the potatoes in the furrow formed by the coulter. This can be achieved by installing a protective casing on the milling drum. Its function is to deflect and direct the soil chips, produced by the milling blades, into the open furrow. The second stage of seed covering involves forming a small ridge using passive coverers from the soil within the milled strip, followed by final ridge shaping with hilling shares using soil from the inter-row space [1, 7, 8].

This study considers the first stage of potato seed covering – by soil chips formed during the operation of the milling drum.

To model the operation of an individual blade of the milling drum, it is first necessary to define its geometric parameters. The blade has an L-shaped profile and consists of i segments of length L_i, which, together with the milling drum radius R, form corresponding angles β_i. Such blades (both right- and left-curved) are mounted on the milling drum, which rotates with an angular velocity ω_b.

The milling drum performs compound motion: it rotates about its own axis in the horizontal plane (relative motion) and simultaneously moves forward with the machine (translational motion). Thus, a specific point on the blade generates a position vector $\vec{r}$ with respect to the axis of drum rotation. The initial position of the selected blade point has coordinates $(x_0(t); y_0)$, where $x_0(t) = V_m t$ (V_m is the translational speed of the machine and t is time).

Therefore, the coordinates of an arbitrary point on the cutting edge of the blade in parametric form can be expressed as:

$$\begin{cases} x(t) = x_0(t) + \left(L_1 \cos\beta_1 + L_2 \cos\beta_2 + L_3 \cos\beta_3\right)\cos\omega_b t; \\ y(t) = y_0 + \left(L_1 \cos\beta_1 + L_2 \cos\beta_2 + L_3 \cos\beta\right)\sin\omega_b t, \end{cases} \quad (1)$$

where $\omega_b t$ is the rotation angle of the blade point on the drum, measured from the horizontal axis of the rectangular coordinate system;

$L_1 \cos\beta_1$, $L_2 \cos\beta_2$, $L_3 \cos\beta_3$ are the projections of the blade segments onto the radius R of the drum, connecting the considered point of the blade to the axis of rotation.

The trajectory of the absolute motion of the blade point is the geometric sum of the horizontal and vertical components of displacement (Fig. 1).

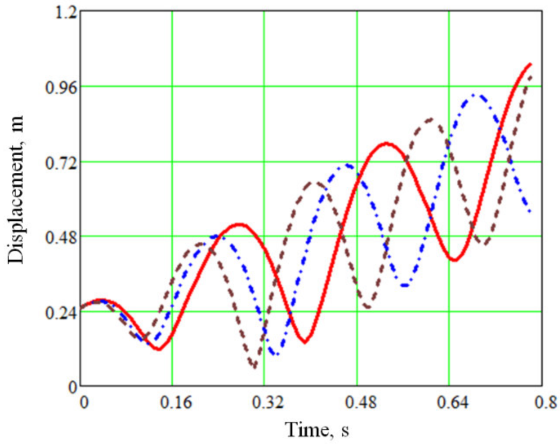

Figure 1 – Trajectory of the absolute motion of the blade point at varying angular velocities
Source: developed by the authors

For the numerical calculation, the following parameters are assumed: the radius of the milling drum $R = 0.25$ m; its rotation frequency is tabulated within the range of 230 to 300 rpm (the solid line corresponds to $\omega_b = 24.09$ rad/s; the dash-dotted line – $\omega_b = 27.75$ rad/s; the dashed line – $\omega_b = 31.42$ rad/s.); the forward speed of the machine $V_m = 0.5$ m/s.

To analyze the considered process, it is first necessary to examine the kinematic parameters of an individual milling's blade during operation.

If equations (1) describe the spatial position of a blade point, then the velocity vector of the blade's contact point with the soil is determined by the following expression:

$$\vec{\vartheta} = \frac{d\overrightarrow{r(t)}}{dt} = \frac{d}{dt}\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \end{bmatrix}. \tag{2}$$

By taking the time derivatives t of expressions (1), we obtain the components of the blade point velocity in expanded form:

$$\begin{cases} \dot{x}(t) = V_m - \omega_b \sin(\omega_b t)\left(L_1 \cos\beta_1 + L_2 \cos\beta_2 + L_3 \cos\beta_3\right); \\ \dot{y}(t) = \omega_b \cos(\omega_b t)\left(L_1 \cos\beta_1 + L_2 \cos\beta_2 + L_3 \cos\beta_3\right). \end{cases} \tag{3}$$

The change in the absolute velocity of the blade point is also characterized by the geometric sum of its horizontal and vertical components

$$\vartheta_n = \sqrt{\dot{x}(t)^2 + \dot{y}(t)^2} \,. \tag{4}$$

It is now necessary to analyze the behavior of a soil particle that moves freely after detaching from the blade edge. This motion can be considered as a free flight of a particle projected at an angle.

The initial velocity of the particle as it leaves the blade can be generally represented by the following expression:

$$\vartheta_0 = k\vartheta_n \,, \tag{5}$$

where $k \in [0.5, 0.9]$ is the coefficient characterizing the energy transfer from the blade to the particle, which depends on the soil properties. In this study, we assume $k = 0.8$.

Since no additional constraints are applied in this model yet, the particle's flight trajectory will initially be analyzed using the classical equations of projectile motion at an angle to the horizontal [3]:

$$x_\alpha(t) = x_{0\alpha} + \vartheta_{0\alpha} \cdot \cos\alpha \cdot t; \quad (6)$$

$$y_\alpha(t) = y_{0\alpha} + \vartheta_{0\alpha} \cdot \sin\alpha \cdot t - 0.5gt^2, \quad (7)$$

where $x_{0\alpha}$, $y_{0\alpha}$ are the coordinates of the particle's initial detachment point from the blade; α is the particle's launch angle ($t = t_{0\alpha}$)

$$\alpha = \arctan\left(\frac{\dot{y}(t)}{\dot{x}(t)}\right) \quad (8)$$

From a kinematic point of view, the detachment point will be considered as the moment when the blade exits the soil while operating at a working depth h (we assume $h = 0.06$ m).

Based on this, it is necessary to find the position of the milling drum $\varphi_{0\alpha} = \omega_b t_{0\alpha}$ or the time $t_{0\alpha}$ at which the considered point is at the soil surface boundary. This position corresponds to the initial coordinates of the soil particle's launch – ($x_{0\alpha}$; $y_{0\alpha}$).

It is advisable to determine this position using the relationship that connects the central angle θ of a circle with radius R (the trajectory of the blade point) to the height h (the millage depth) of the segment formed by this circle.

The central angle θ in this case will be given by

$$\theta = 2\arccos\left(1 - \frac{h}{R}\right). \quad (9)$$

Then, half the length of the chord of this segment, which corresponds to the horizontal displacement of the blade, will be equal to

$$x_h = R\sin\frac{\theta}{2}. \quad (10)$$

Based on the first equation in (1), we write the expression to determine the time $t_{0\alpha}$

$$t_{0\alpha} = \frac{1}{\omega_{b\alpha}}\arccos\left(\frac{x_h}{R}\right), \quad (11)$$

where $\omega_{b\alpha}$ is the angular velocity of the milling drum, which determines the time when the blade exits the soil at the given working depth h.

The coordinates of the detachment point will be:

$$x_{0\alpha} = R\cos(2\pi - \omega_{b\alpha} t_{0\alpha}); \quad (12)$$

$$y_{0\alpha} = R\sin(2\pi - \omega_{b\alpha} t_{0\alpha}). \quad (13)$$

The obtained coordinates of the detachment point depend on the blade position, considering that it exits the soil in the fourth quadrant of the coordinate axis at the working depth h.

The detachment angle of the particle is denoted by $2\pi - \omega_{b\alpha} t_{0\alpha} = \varphi_{0\alpha}$.

The components of the initial velocity will be determined at the blade position corresponding to the particle launch:

$$\vartheta_{x0\alpha} = -\omega_b R \sin\varphi_{0\alpha}; \quad (14)$$

$$\vartheta_{y0\alpha} = \omega_b R \cos\varphi_{0\alpha}. \quad (15)$$

In general, the moment when the blade reaches the soil surface is characterized by the velocity ϑ_0 – the initial velocity of the particle's flight at an angle α to the horizontal, denoted as $\vartheta_{0\alpha}$. This velocity is the geometric sum of the horizontal and vertical components of velocity at time $t_{0\alpha}$

$$\vartheta_{0\alpha} = k\sqrt{\dot{x}(t_{0\alpha})^2 + \dot{y}(t_{0\alpha})^2}\,. \quad (16)$$

To determine the angle α at which the particle is ejected, expression (8) can be rewritten in the form

$$\alpha = \arctan\left(\frac{\dot{y}(t_{0\alpha})}{\dot{x}(t_{0\alpha})}\right) \quad (17)$$

Having obtained the value of the angle α, the horizontal and vertical components of displacement during the free flight of a soil particle ejected from under the milling's blade can be expressed based on relations (6) and (7). The graphical interpretation of the trajectory components of the particle's free flight is shown in Fig. 2.

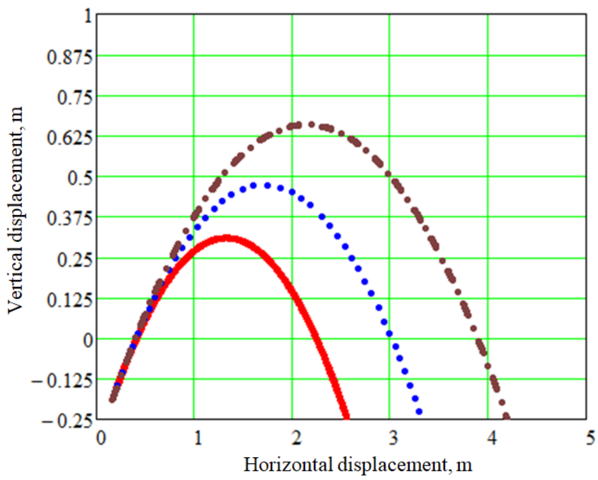

Figure 2 – Trajectories of free flight of soil chips

Source: developed by the authors

Thus, at this stage of the study, the main dependencies characterizing the free flight of a soil particle - soil chips during the operation of the milling drum were established and free flight trajectories were constructed at a given frequency of rotation of the working body.

Returning to the main objective of the work – the possibility of covering potato seed with the formed soil chips – we summarize the process as follows:

– soil moves along a parabolic trajectory after leaving the blade;

– particles collide with a protective casing having a radius of curvature R_k, centered at coordinates x_{0k}, y_{0k};

– after impact with the casing, a particle either rebounds or slides down, falling at a certain landing point x_f.

Therefore, it is necessary to select the shape and placement of the protective casing such that the majority of the scattered or reflected soil particles fall into the zone of the potato seed placement, that is

$$x_f \in \left[x_k - \delta, x_k + \delta\right], \tag{18}$$

here, x_k denotes the coordinate of the potato seed placement and $\pm\delta$ represent the boundaries of the soil covering zone.

The next stage of the study is to determine the behavior of the particle after collision with the guiding protective casing.

The collision between the soil particle and the casing occurs at the moment when

$$y_\alpha(t) = f(x(t)). \tag{19}$$

Using condition (19), the collision time is determined.

The subsequent trajectory of the particle depends on the point of curvature of the casing where the collision occurs.

Upon impact with the curved surface of the casing, the velocity vector decomposes into two components:

the normal component

$$\overrightarrow{\vartheta_n} = \left(\vec{\vartheta} \cdot \vec{n}\right)\vec{n}; \tag{20}$$

the tangential component

$$\overrightarrow{\vartheta_t} = \vec{\vartheta} - \overrightarrow{\vartheta_n}, \tag{21}$$

where $\vec{n}$ is the unit normal vector to the surface at the point of impact.

Then, after the collision, the particle will have a new velocity determined by the expression

$$\overrightarrow{\vartheta_s} = -e\overrightarrow{\vartheta_n} + \mu\overrightarrow{\vartheta_t}, \tag{22}$$

where e is the coefficient of restitution, characterizing the elasticity of the impact, which ranges between $e \in [0,1]$;

μ is the coefficient of friction of the soil chips on the surface of the casing.

If the velocity after rebound is insufficient to form a new parabolic flight trajectory, the particle simply falls off or slides along the casing surface.

Its acceleration will be

$$\frac{d\vartheta_s}{dt} = g\sin\theta_k - \mu g\cos\theta_k, \tag{23}$$

where θ_k is the local inclination angle of the casing at the point.

If we analyze the process of covering the planted potato in the furrow, it is continuous. The cutting and falling of soil chips occur constantly, as the machine moves in translational motion. Soil covers not only the planted seed but also fills the furrow opened by the coulter.

Therefore, the outlined problem can ultimately be reduced to verifying the curvature and placement of the guiding casing by setting the condition of ideal reflection of a soil particle from its surface at a given moment in time and directing it into the target zone. This is done to prevent the particle from returning after reflection back into the milling zone.

Particles that do not meet the condition of ideal reflection will slide down the casing surface, which physically guides them into the furrow.

This means that the geometry of the casing must prevent the particle from reflecting backward and instead direct it into the target zone. Considering a local moment in time, the reflected particle that reaches the furrow level should have coordinates $[x_k - \delta, y_k]$, that is, its new trajectory must pass through this point.

Therefore, it is advisable to consider the inverse problem: to find the position of the section of the casing curve such that the contact points of the scattered flight trajectories of the soil chips, upon reflection, fall within the target zone.

To this end, we will analyze the initial conditions for forming the trajectory of the reflected particle's motion.

Let us find the collision point of a particle moving along a parabolic trajectory with a casing of given curvature:

$$\begin{cases} x_\alpha(t) = x_{0\alpha} + \vartheta_{0\alpha} \cdot \cos\alpha \cdot t; \\ y_\alpha(t) = y_{0\alpha} + \vartheta_{0\alpha} \cdot \sin\alpha \cdot t - 0.5gt^2; \\ y(t) = f(x(t)). \end{cases} \quad (24)$$

Based on system (24), we derive a nonlinear equation with respect to time t

$$y_{0\alpha} + \vartheta_{0\alpha} \cdot \sin\alpha \cdot t - 0.5gt^2 = f(x_{0\alpha} + \vartheta_{0\alpha} \cdot \cos\alpha \cdot t)). \quad (25)$$

Its solution is most easily implemented using a numerical method, but first, it is necessary to define the curve describing the cross-section of the casing.

The most practical function may be a polynomial curve, for example, of the third degree

$$y(t) = f(a_3 x(t)^3 + a_2 x(t)^2 + a_1 x(t) + a_0), \quad (26)$$

where a_i are the coefficients that define the specified curvature on the designated segments of the polynomial curve ($i = 0...3$).

The root of equation (25), taking into account (26), will be the time $t = t_K$ corresponding to the moment and point of collision, that is $K = (x(t_K), y(t_K))$.

The tangent to the curve (26) at point K is given by its derivative

$$f'(x) = \frac{dy}{dx} = 3a_3 x^2 + 2a_2 x + a_1. \quad (27)$$

Relation (27) expresses the slope of the tangent at any point x on the casing.

The tangent angle at point K is

$$\theta_t = arctg(f'(x_K)), \quad (28)$$

accordingly, the angle of the normal is

$$\theta_n = \theta_t + \frac{\pi}{2}. \quad (29)$$

Then, given the known velocity at point K is $\vec{\vartheta}_K = (\vartheta_x, \vartheta_y)$, the angle of its motion will be

$$\theta_K = arctg2(\vartheta_x, \vartheta_y). \quad (30)$$

In the problem statement, it was assumed that the particle undergoes ideal reflection – corresponding to the trajectory with the maximum possible deviation, where the particle can reflect toward the milling zone. In this case, the reflection angle of the particle at point K will be

$$\theta'_K = 2\theta_n - \theta_K. \quad (31)$$

The obtained values of the reflection θ'_K, the velocity at point K and its coordinates serve as the initial conditions for the particle's flight trajectory after reflection until it lands on the soil surface. The trajectory construction can be performed using relations analogous to (6) and (7).

Analyzing the obtained flight trajectories of the particle (Fig. 2), it is evident that the segments before collision with the casing have an almost linear character. Based on this and using relation (26), a first approximation of the casing shape can be obtained that satisfies the condition of targeted guidance of soil chips (Fig. 3).

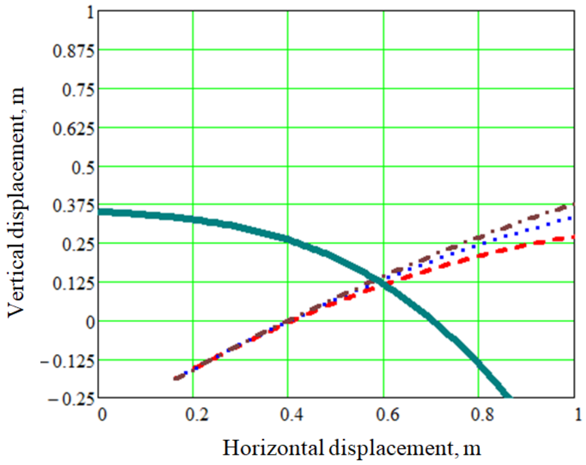

Figure 3 – Graphical dependencies for the study of the casing shape

Source: developed by the authors

In Fig. 3, the dash-dot line, the dotted line formed by points and the dashed line represent the flight trajectories of the soil particle corresponding to those in Fig. 2, while the thick solid line depicts the curve describing the shape of the casing.

The analytical expression for the casing curve is given by

$$y(x) = -0.78x^3 - 0.034x^2 - 0.089x + 0.35. \quad (32)$$

Adjusting the coefficients a_i or even using higher-order polynomials, allows selecting a shape of the casing curve or its segment that ensures directing the soil chips into the target zone. This means that, with such an approach, it is possible to achieve the effect of primary covering of potato seeds during strip milling in the design of a potato planting machine.

Conclusions.The presented methodology allows for describing the geometric and kinematic parameters of the milling drum blade, which is formed by several segments; determining the ejection point of soil chips from under the blade, taking into account the working depth; modeling the flight trajectory of soil chips with given initial velocity and launch angle; investigating the range of trajectory dispersion under various parameters and identifying the points and angles of interaction between soil particles and the guiding casing.

A polynomial function is proposed to describe the casing curve, where adjusting the coefficients ensures the specified curvature over certain segments. This approach enables combining theoretical solutions with practical implementation in the physical design of a potato planting machine.

The process of particle interaction with the casing is described, including reflection, sliding, and falling off. The dependencies of the tangent line at a given point on the casing curve are formulated, and based on this, the reflection angle of the particle upon collision with the casing is determined.

For the physical design of the milling module of the potato planting machine, parameters of the casing curve have been established that allow reflecting and directing soil chips into the target zone for the primary covering of potato seeds. The achieved effect in this numerical experiment can be obtained for the given design and kinematic parameters of the milling module using the following coefficients of the polynomial curve (26) for the casing: $a_3 = -0.78$; $a_2 = -0.034$; $a_1 = -0.089$; $a_0 = 0.35$.

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Обґрунтування параметрів модуля підготовки ґрунту картоплепосадочної машини

У статті наведено обґрунтування конструктивних та кінематичних параметрів модуля підготовки ґрунту у складі картоплепосадочної машини, що здійснює смугове фрезерування та забезпечує первинне присипання насіння картоплі. Розроблено методику, яка дозволяє описати геометричні та кінематичні характеристики фрезерного барабана з ножами складної форми, визначати початкові умови вильоту ґрунтової стружки, моделювати її траєкторію руху та взаємодію з поверхнею направляючого кожуха. Встановлено аналітичну залежність для опису кривизни кожуха, яка забезпечує спрямування ґрунтових частинок у цільову зону, де розміщене насіння.

Актуальність роботи зумовлена потребою у підвищенні рівня механізації процесів садіння картоплі в умовах дрібних фермерських та приватних господарств України, де сконцентровано значну частину валового виробництва картоплі. Підвищення якості посадки та забезпечення необхідної структури ґрунту у зоні розміщення насіння є важливою умовою для отримання високих урожаїв.

У роботі показано, що смугове фрезерування є енергоощадною та агротехнічно доцільною технологією підготовки ґрунту при посадці картоплі. Проте для досягнення ефекту первинного присипання насіння ґрунтовою стружкою, необхідно враховувати не лише конструкцію ножа, а й характер руху частинок ґрунту після їх вильоту. Тому у роботі запропоновано модель, яка дозволяє визначати координати та кінематичні характеристики ґрунтових частинок при їх зіткненні з направляючим кожухом, а також умови їх подальшого руху – відбивання, осипання чи ковзання.

Розроблений підхід дає можливість забезпечити раціональну форму кожуха, що виконує функцію перенаправлення ґрунтової стружки у цільову зону борозни. Загалом, комбінування різних модулів в одному агрегаті дозволяє об’єднати процеси підготовки ґрунту, посадки з підживленням, початкового та остаточного прикривання насіння в одному технологічному проході, що підвищує ефективність та якість посадки.

насіння картоплі, ґрунтова стружка, посадка, смугове фрезерування, параметри, моделювання, аналіз, направляючий кожух, траєкторія польоту, подрібнення, розпушення

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