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PHYSICAL METHODS OF PRE-PLANTING AND POSTHARVEST TREATMENT OF POTATO: A REVIEW

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Abstract. Potato is an important staple food crop. Potato tubers require proper treatment before planting and after harvest to produce high yields and avoid storage losses. Among different techniques of potato treatment physical methods are of special interest: thermal treatment using hot water and steam, ultraviolet (including continuous-wave UV using pulsed Xe-lamps) and gamma-irradiation, treatment with magnetic and electromagnetic fields (including microwaves). The majority of physical methods is environmentally friendly and can be applied without special registration and in the developing countries. In the present paper, for the first time, the scientific papers on physical methods of potato treatment for the last 35 years are comprehensively reviewed. The review demonstrates that such an approach is perspective both for pre-planting and postharvest treatment of potato. Physical treatment affects biochemical, cellular and physiological status of potato. Methods of physical treatment enable to control phytopathogens, and some methods (ultraviolet and gamma-radiation) even are capable of improving immunity of plants. The main traits of potato tubers that can be influenced by physical treatment are sprouting (stimulation or inhibition), susceptibility to rot and black leg diseases, and starch, reducing sugars and ascorbic acid contents. The tuber response to physical treatment depends on dosage and date of treatment, duration and temperature of storage, agricultural technology and cultivar. Low doses of treatment may be inefficient while too high dosage may result in cell deterioration or death and poor immunity, and eventually to disease development. Too early treatment may damage a tuber since it should pass through suberization (wound healing) after harvest; too late treatment requires higher doses. The proper adjustment of treatment is necessary for cultivar and individual storage conditions.

Key words: potato, physical treatment, hydrothermal treatment, steam, ultraviolet, xenon lamp, gamma-irradiation, electromagnetic microwaves, phytopathogen

INTRODUCTION

Potato tubers require proper treatment before planting, after harvesting and at storage to produce high yields and avoid storage losses. Different methods are used to reduce infection, promote sprouting or keep dormancy, maintain required physiological and biochemical status of a tuber.

There are different methods of potato tuber treatment, such as chemical, biological, breeding, and physical; application of them is determined by the aim and the cost of technique. Physical treatment does not require complicated technologies such as chemical synthesis or development of new potato varieties or new bacteria strains and can be afforded by developing economies. In addition, it is ecological friendly and does not affect consumer health. Then, some physical methods may be competitive to genetic and chemical modifications as they do not require registration or special permission and may be more effective in certain aspects. On the other hand, such practices as hot dry, steaming, UV and gamma radiation are far from introduction at industrial scale as technologies and are still perspective and promising approaches. Moreover, each physical method if applied at improper dosage can damage or even kill a tuber so it is crucial to find a proper time and dose in each case depending on the aim of treatment and cultivar.

The aim of this paper is to review the achievements in physical treatment methods of potato.

TEMPERATURE TREATMENT

Hot water treatment of potato tubers significantly reduces rot bacteria contamination [1]. Mackay and Shipton [2] did not detect *Pectobacterium atrosepticum* and *P. carotovorum* subsp. *carotovorum* in tuber peel after dipping naturally infected potato tubers for 10 min in water at 55 °C as well as no blackleg symptoms were observed in plants grown from the treated tubers. Similarly, Wale and Robinson [3] and Shirsat et al. [4] showed that periderm and lenticels contamination can be significantly reduced by incubation in water at 44 °C for 30 min or at 56 °C for 5 min. However, if insufficiently dried out, the tubers may rot due to multiplication of survived bacteria. Drying tubers under forced ventilation with air knives may help to overcome this problem not only removing water from tuber surface but also keeping heat [5]. Hydrothermal treatment helps to control several fungal pathogens causing gangrene, skin spot, silver and black scab [6]. Abbas et al. [7] showed that treatment of tubers with hot water at 37 °C for 2—3 hours reduces Potato Leaf Roll Virus in plants grown from them by up to 37%. However, hydrothermal treatment may lead to delay in sprouting or even death of tuber depending on the physiological state and eventually to yield losses [1].

Steam can be used as an alternative to hot water to control fungi and bacteria especially *P. atrosepticum* and *P. carotovorum* present in tuber periderm. Steam treatment reduced periderm contamination from 26 ... 59% to 1 ... 3% [8]. Bartz and Kelman [9] observed that external population can be eliminated by hot air dry at 50 °C. Hot air dries tubers and stimulates wound healing without affecting subsequent sprouting. However, longer incubation time required for steam treatment compared to hot water can adversely affect a tuber [1].

Lavrova et al. [10] studied the effect of pre-planting cool treatment on seed tubers artificially infected with nematodes: sprouted tubers were kept at +5 °C for 2 hours during 6 days. As a result, yield quantity and quality (starch and ascorbic acid content) were improved when potato was grown on infested soils. Eremeev et al. [11] showed that pre-planting heat shock at 30 °C for 2 days with subsequent keeping at +12 ... +15 °C for 5 days in the light make it possible to get more tubers 5—10 days earlier than in the control that may be explained by increasing physiological age of the seed tubers.

SHORT-WAVELENGTH ULTRAVIOLET IRRADIATION

Short-wavelength ultraviolet light (UV-C) has strong antimicrobial effect. It provokes single and double-strand breaks in DNA, producing thymine dimmers and 4,6-photoproduct as well as reactive oxygen species. The resulted DNA lesions interfere with replication and transcription, eventually disabling or killing microorganisms [12—15]. Additionally, the UV-C light results in tryptophan, tyrosine, phenylalanine and cysteine oxidation with subsequent degradation and DNA-protein bonds that inhibit cell survival and proliferation [16].

The UV-C rays cover the wavelength range 100—280 nm, in practice mercury-vapor lamps (Hg-lamps) with a strong emission line at 254 nm are widely used for disinfection purposes. The UV-C energy is unable to penetrate tuber tissue to reach the vascular pathogens and therefore can be used for surface microorganisms mainly [1].

The UV-C irradiation at 10 kJ m^{-2} reduces incidence and severity of common scab by 28% and 62%, respectively, while silver scab is inhibited at 15 kJ m^{-2} by 22% and 36%, respectively [17]. Ranganna et al. [18] demonstrated that UV-C irradiation at 15 kJ m^{-2} inhibits soft and dry rot in the tubers inoculated with *Fusarium solani* and *P. carotovorum* at +8 °C for 3 months. However, the inhibition efficiency of UV-C dropped at longer inoculation of the tubers. Rocha et al. [19] observed that the UV-C treatment at 34.5 kJ m^{-2} significantly reduced postharvest soft rot incidence by 60% in potato seed tubers stored at +25 °C for 9 days after inoculation with *P. carotovorum* subsp. *carotovorum*. However, the disease was completely inhibited both in untreated and UV-C-treated tubers when they were stored under fluorescent light (280 ... 400 nm, UV-A + UV-B; 1.6 μmol m^{-2} s^{-1}). The disease inhibition may be associated with the accumulation of α-solanine and α-chocanine glycoalkaloids in periderm and flesh in UV-C- and fluorescent light treated tubers. Thus, the UV-C irradiation affects not only surface microorganisms but also tuber periderm layer changing its biochemical status, thus enhancing its immunity.

Besides disinfection of tubers the UV-C treatment can be used for potato tuber dormancy regulation at storage. Conventionally, low positive temperatures and ethylene are used to inhibit sprouting, but these techniques can give rise to high sugar concentrations reducing the processing quality of potatoes [20—22]. Cools et al. [23] demonstrated that sprouting inhibition in response to the UV-C treatment is cultivar specific. Tuber sprouting of the most sensitive to UV-C irradiation cultivars was inhibited at 10 kJ m^{-2} and associated with increase in ascorbic acid level; the strongest effect appeared at 10% eye movement. However, even at such high dose as 30 kJ m^{-2} authors did not find sprouting stimulation as it was observed in other experiments [9, 24, 25]. The UV-C treatment at 3.4 ... 13.6 kJ m^{-2} significantly reduced number of spouts in the irradiated tubers if stored at +20 °C for up to 20 days [26].

The UV-C treatment can affect biochemical parameters of tubers. Hg-lamp irradiation at 15 kJ m^{-2} changed neither texture nor color of a tuber as well as did not damage starch granules [25]. Cools et al. [23] did not found DNA degradation or cyclobutane pyrimidins in periderm of the tubers irradiated at 5 ... 30 kJ m^{-2}. The total reducing sugar content in the UV-C-treated tubers was 1.65 ... 2.02 fold lower compared to the untreated control after storage at +4 °C for 28 days. Lin et al. [27] suggest that the UV-C treatment possibly regulates the gene cascade in potato tuber (sucrose phosphate synthase, invertase inhibitor 1/3, and invertase 1) that reduced accumulation of reducing sugars and prevented oxidative injury in potato cells.

CONTINUOUS-WAVE ULTRAVIOLET RADIATION

Mercury-free pulsed xenon lamp (Xe-lamps) can be used as an alternative to Hg-lamp. Xe-lamp is characterized by continuous emission spectrum (190 ... 400 nm, i.e. UV-A, UV-B and UV-C) that provides bactericide effect to the irradiated objects independent from the absorption spectrum at a shorter exposition time compared to Hg-lamp. The efficiency of the continuous-wave pulsed UV-light was proved for water disinfection [28, 29]. The advantages of Xe-lamps allow them to be widely used for disinfection purposes in different spheres: food production and storage [30, 31], disinfection of surfaces [32], and packaging [33].

To estimate the Xe-lamp irradiation effect on the integrity of DNA of *Dickeya solani*, pathogen causing potato blackleg, Kroupin et al. [34] performed quantitative polymerase chain reaction (qPCR). It was shown that each genomic 100 bp is damaged by ~10 J m^{-2}. The comparison of bactericide effects of Hg- and Xe-lamps demonstrated that Xe-lamp damages 4.9% of *D. solani* genome at 10 kJ m^{-2} while Hg-lamp only 1.5% at the same dose; unlike Hg-lamp, Xe-lamp irradiation resulted in protein degradation and aggregation [35]. The experiments on potato slices showed that Xe-lamp irradiation at 12 kJ m^{-2} almost totally inhibited the rot development while Hg-lamp irradiation even at 36 kJ m^{-2} resulted in the rot spot diameter three fold larger than that in the Xe-lamp variant [36, 37]. Further study of Xe-lamp irradiation may show its perspective in controlling pathogens as well as its effect on physiological and biochemical status of potato tubers.

Both UV-C and continuous-wave UV-irradiation can be used not only for tuber treatment but also for hygienic measures such as disinfection of irrigation water, machines and tools, storage and package.

GAMMA IRRADIATION

High-energy ionizing radiation affects enzyme activity, protein synthesis, metabolic processes in the cell, cell division, differentiation, hormone balance and gas exchange. As a result, considerable changes can occur in the tuber dormancy, starch, sugar and ascorbic acid content and, eventually, technological and custom properties of the tuber. Depending on the dose gamma irradiation may either induce or inhibit metabolic processes in the tuber, having some antimicrobial effect.

Stimulation effect of low gamma irradiation doses

Low doses of gamma radiation can be used for potato *in vitro* propagation to stimulate tuber formation. Al-Safadi et al. [38] found that irradiation at 2.5 Gy simulates microtuber production *in vitro* by up to 38% in comparison to untreated plantlets without fear of genetic changes in the used cultivars. Li et al. [39] demonstrated that irradiation of the potato plantlets *in vitro* significantly stimulated microtuberization by 116.7% and 34.5% in the studied cultivars compared to the non-irradiated control and increase in fresh mass. Low doses (2 ... 3 Gy) increased starch content; medium doses (4 ... 6 Gy) increased protein content; higher doses (6 ... 8 Gy) increased ascorbic acid and reducing sugars in microtubers.

Moderate doses can be applied to stimulate sprouting of tubers with low germination ability, e.g. in maintenance of genetic stocks. Salomon et al. [40] demonstrated the stimulation effect of 20 Gy on germination of botanical seeds while Tikhonov et al. [41] observed the stimulation effect of 50 Gy on seed tubers.

Inhibiting effect of high gamma irradiation doses

The main goal of storage is to keep dormancy as close to postharvest level as it is possible. Second task is to keep starch content at the initial level. The sprout of tuber buds enhances respiration and induces enzymatic hydrolysis of the starch. Low temperature inhibits sprouting but results in accumulation of reducing sugars (‘cold-induced sweetening’), which induce discoloration of potato chips or French fries [42]. Ionizing irradiation inhibits sprouting without using low temperatures at storage. It is especially critical for south regions with warm postharvest seasons. The third task is to keep tubers free from rot during storage period. Moderate gamma-irradiation doses may promote immunity response in the tuber, while too high doses may damage tissues and result in tuber rot.

The recommended gamma irradiation dose for sprout suppression varies from 40 ... 50 Gy to 120 ... 150 Gy [43—47]. The dose sufficient for sprout inhibition is apparently cultivar specific. For example, the total inhibition in cv. Lorkh and cv. Lyubava tubers was observed at dose higher than 18 Gy and 21 Gy, respectively [48].

Moderate gamma irradiation inhibits rot and scab severity. Tikhonov et al. [41] observed inhibition of silver scab after gamma irradiation at 100 Gy, whereas dose increase up to 150 Gy resulted in the development of common scab, silver scab and ring rot that may be explained by the inhibition of the tuber cell immunity at higher doses. Afify et al. [49] demonstrated that 50 Gy inhibits sprouting without causing rot that may be associated with high antioxidant enzyme activities (peroxidase, polyphenol oxidase, glutathione-S-transferase, superoxide dismutase, and catalase) and the lowest level of lipid peroxidaiton. Mahto et al. [46] suggests that the rot suppression at 150 Gy may be due to higher polygalacturonase-inhibiting protein activity in non-sprouted tubers compared to the sprouted tubers.

At higher gamma irradiation doses the cell wall and membrane are disrupted; rot development, water loss, skin and flesh darkening, bud blackening and tuber softening are observed. In most studies the destructive processes are shown at doses higher than 1 kGy [44, 50, 51]. Apparently, 500 Gy is the highest acceptable (threshold) dose and depends on the cultivar and tuber condition [46, 47]. Since bud tissues in eyes are meristematic and are least tolerant to gamma irradiation, their blackening occurs at 500 Gy [46]. Tuber lots with high rot potential may not be suitable for gamma irradiation treatment at all [43].

The date of tuber treatment (days after harvest, DAH) is critical: periderm is very susceptible to high irradiation doses immediately after harvesting and tuber should pass through suberization. The day of treatment influences the accumulation of sugars in tuber. Dhali et al. [47] showed that 150 Gy 15 DAH resulted in less sugar accumulation during 2 months of storage rather than treatment 30 DAH. Rezaee et al. [45] demonstrated that the later the treatment (10, 30 and 50 DAH were compared), the more sugar is accumulated after 5 months of storage both at +8 °C and +16 °C. After 120 days of storage tubers irradiated 5 DAH contained less reducing sugars than that 30 DAH [50].

The day of treatment determines the dose of gamma irradiation: the latter the treatment the higher dose is required. Treatment at low dose (40 Gy) on 6 DAH inhibits sprouting stronger and does not accompanied with shriveling compared to treatment on day 30 after harvest; treatment at both 80 and 120 Gy 5 and 30 DAH showed good tuber appearance [50]. Rezaee et al. [45] showed that treatment 10 DAH totally inhibits sprouting at 100 Gy; the irradiation dose for treatment 30 and 50 DAH should be raised up to 150 Gy. Dhali et al. [47] observed that weight loss of tubers irradiated 15 DAH is less than 30 DAH (150 Gy, 2 month of storage).

Temperature of storage is crucial since it is gamma irradiation make it possible to store potato tubers at moderate-to-high temperatures without accumulation of reducing sugars as it happens at low temperature storage. The higher the temperature of storage, the less sugar is accumulated in tubers. Dhali et al. [47] showed that tubers exposed to 150 Gy and subsequently stored at +6 °C for 2 months contained more sugars compared to +15 °C. Rezaee et al. [45] found that tubers irradiated at 100 Gy and subsequently stored at +8 °C accumulated more sugars than that at +16 °C. Ezekiel et al. [52] demonstrated the response to the storage temperature was cultivar specific: cv. Kufri Jyoti contained less reducing sugars at +16 °C than at +8 °C by 34%, whereas cv. Kufri Chandramukhi by 15% (150 Gy, 90 days of storage). Rezaee et al. [45] suggests that less sugar content at higher storage temperature may be due to higher respiration rates. In addition, temperature influences weight loss: weight loss was higher if tubers were stored at +16 °C than at +8 °C (100 Gy, 5 months of storage); these losses can be compensated by dose increase to 150 Gy.

Gamma irradiation may affect the integrity of starch granules and amylose and amylopectin molecules and the response of the cell may be cultivar specific [50, 52]. Ezekiel et al. [52] showed that the degradation of starch and, as a consequence, changes in sugar accumulation and amylose content after irradiation at 500 Gy was specific for each of three cultivars studied. Mahto et al. [46] found that cv. Kufri Sindhuri is characterized by increase in the textural parameters after irradiation at 500 Gy and storage at +12 °C for 120 days compared to cv. Kufri Jyoti. Cell wall remained rigid, accounting for higher textural values registered after treatment at 120 Gy and storage at +22 °C for 4 months; exposition to 1 kGy induced damage and resulted in more collapsed cells with less rigid cell walls [50].

The dose of gamma-irradiation affects the ascorbic acid content in tubers. The increase in irradiation dose resulted in drop in ascorbic acid in tubers when stored at +15 °C and +16 °C, respectively [45, 47].

Gamma irradiation leads to rise in amylose content [52, 53]. Lu et al. [53] suggests that it may be associated with the effect of gamma-rays on the branched molecules of amylopectin susceptible to low radiation dosage; the newly de-branched amylopectin chains contributed to the amylose content. At extreme dosage both amylose and amylopectin molecules are depolymerized and thus the starch shows the decreased amylose content [54, 55]. Tubers exposed to 150 Gy and stored at +24 °C for 35 days showed the starch content at the level of the untreated control [51]. Lu et al. [53] showed that starch content significantly decreased in two studied cultivars irradiated at 100 Gy and stored at +8 °C for 5 months.

Irradiation dose affects sugar content in tubers: the higher radiation, the higher sugar content. Apparently, sugar molecules are a product of starch glycoside bonds breakage by gamma-rays [54]. Frazier et al. [43] demonstrated that a dramatic raise in sugar content occurs after irradiation at 20 ... 40 Gy and storage at +7.2 °C; then the sugar content is normalized to the untreated control level in 210 days if stored at +7.2 °C or in a month if stored at +15 °C. The content of reducing sugars in tubers exposed to 1 kGy was 1.3 fold lower than at 80 Gy when stored at +22 °C for 120 days [50]; glucose content in tubers at 2 kGy was 1.8 fold higher than at 150 Gy when stored at +24 °C for 35 days. The glucose content dynamics through storage is cultivar specific: raise in glucose content in tubers of cv. F03031 and F03028 exposed to 100 Gy and stored at +8 °C was 1.5 and 2 fold, respectively; cv. Shepody did not show significant changes in glucose content [53]. Tubers of cv. Kufri Jyoti and cv. Kufri Chandramukhi treated at 500 Gy and stored at +16 °C contained 20% and 5% reducing sugars more than at 100 Gy, respectively.

Thus, the gamma irradiation treatment of potato tubers at moderate dosage (40 ... 150 Gy) should be thoroughly optimized. The main advantages of gamma irradiation are the inhibition of sprouting, the opportunity to store treated tubers at moderate (15 ... 22 °C) temperature and rot and scab control. On the other hand, the increase in dose results in raise in reducing sugar and amylose content, loss in starch and ascorbic acid content, drop in weight mass and specific gravity, rot development due to cell structure damage. The dosage, date of treatment (day after harvest), and temperature should be properly adjusted depending on a particular cultivar and storage duration.

MAGNETIC AND ELECTROMAGNETIC TREATMENT

Magnetic field can be used for tuber disinfection to promote sprouting of seed tubers and for postharvest treatment.

Pre-planting electromagnetic microwave irradiation of seed tubers at 10 kJ m^{-2} decreased significantly the incidence of round rot in the yield by 35%; irradiation at 1 kJ m^{-2} inhibited strongly common and silver scab incidences by 30% and 28% and severity by 40% and 11%, respectively. Postharvest treatment at 15 kJ m^{-2} reduced the incidence of round rot by 80% whereas 6 kJ m^{-2} did not affect the disease incidence [17].

Marks et al. [56] observed stimulation of length and number of stems, foliage and stem mass, and tuber sprouting index by canopy treatment with variable magnetic field.

Tikhonov et al. [17] found that small dosage of electromagnetic microwaves stimulated growth of sprouts that became more competitive to parasitic mycelium. Vasiliev et al. [57] showed the effect of electromagnetic microwave field on yield and starch content in tubers; the effect depended on the agricultural techniques used in the field experiments. The dosage of variable electromagnetic field affects the losses of tuber weight during storage at +25 °C for 16 days: the losses at 6 ... 8 mTs did not exceed 20% whereas at higher doses they raised to 75% compared to 39% in the untreated control [58].

OTHER PHYSICAL TREATMENTS

There are other perspective methods of potato tuber treatment studied in papers: helium plasma [59], treatment with modulated low-frequency electric field [60] and others.

CONCLUSIONS

In conclusion, the following physical treatment approaches have been studied for the last 35 years: steam and hot water, ultraviolet (UV-C and continuous-wave UV) and gamma irradiation, magnetic field. High-temperature treatment with hot water or steam can be used mainly to control blackleg. Treatment with high frequency waves (microwaves, gamma and ultraviolet irradiation) is characterized by more complex effect on tuber: disinfection (especially blackleg, scab and rot), immunity enhancing/suppression, sprouting stimulation/suppression, changes/maintenance of biochemical compounds content. The crucial parameters for physical field treatment are the proper adjustment of the dosage, date and storage conditions. Too low dosage may be insufficient to suppress pathogens, while too high dosage may result in cell wall damage and starch degradation that leads to rots and losses. A special attention should be paid to the influence of treatment on tuber dormancy: sprout stimulation is required for pre-planting treatment while postharvest treatment should inhibit sprouting. Finally, since UV and gamma irradiation are cultivar specific, the treatment technology should be finely adjusted for each cultivar depending on the conditions of growing and storage.

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ФИЗИЧЕСКИЕ МЕТОДЫ ПРЕДПОСАДОЧНОЙ И ПОСЛЕУБОРОЧНОЙ ОБРАБОТКИ КАРТОФЕЛЯ: ОБЗОР

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Картофель является важной продовольственной культурой. Правильная предпосадочная и послеуборочная обработка клубней позволяет получить высокий урожай и избежать потерь при хранении. Среди различных методов обработки картофеля особое положение занимают физические методы: тепловая обработка горячей водой и паром, ультрафиолетовое (в том числе широкополосное) и гамма-облучение, обработка магнитными и электромагнитными полями (в том числе сверхвысокочастотными). Большинство физических методов относительно безвредны для окружающей среды и могут быть использованы без специальной регистрации и развивающимися странами. В статье впервые проведен обзор научных статей за последние 35 лет, посвященных физическим методам обработки картофеля (включая патенты на изобретения). Обзор научных статей показал перспективность данного направления как для предпосадочной, так и послеуборочной обработки картофеля. Физическая обработка оказывает воздействие на биохимический, клеточный и физиологический статус картофеля. Методы физической обработки позволяют контролировать фитопатогены, а отдельные методы (ультрафиолетовая, гамма-радиация) даже способны повышать иммунные свойства. Основные параметры клубней картофеля, на которые влияют методы физической обработки, — это прорастание глазков (стимуляция или ингибирование), поражение гнилью и черной ножкой, содержание крахмала, редуцирующих сахаров и аскорбиновой кислоты. Реакция клубней картофеля на методы физической обработки зависит от дозы, даты обработки, сроков и температуры хранения, агротехники и сорта. Низкие дозы обработки могут оказаться неэффективными, а слишком высокие могут привести к повреждению или гибели клеток и снижению иммунитета, а в конечном счете к развитию заболеваний. Слишком ранняя обработка может повредить клубень, так как после уборки ему необходимо пройти процесс суберинизации (заживления); при слишком поздней требуется повышение доз. При выборе метода физической обработки необходимо тщательно оптимизировать указанные параметры для конкретных условий хранения и сорта.

Ключевые слова: картофель, физическая обработка, гидротермическая обработка, пар, ультрафиолет, ксеноновая лампа, гамма-облучение, электромагнитные микроволны, фитопатоген

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