Vertical vegetable growing: creating tomato varieties for multi-tiered hydroponic installations

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Abstract. The relevance of vertical vegetable growing is due to the need to ensure an uninterrupted supply of food and reduce the cost of food production in terms of moving the majority of the population of the Earth into urban space. The market of vertical vegetable growing can be characterized as capacious and fast-growing. In the Russian Federation, this market is still developing. The main vegetable crops are not represented in it. The purpose of the study was to create tomato varieties for the vertical vegetable growing (multi-tiered hydroponic plants). For this purpose, a new approach to the breeding process was necessary, in which the variety would be considered as an element of the technological chain. A collection of 692 tomato samples served as our research material. Research methods included the following: creating a model of a new form of tomato for multi-tiered hydroponic structures; analyzing the genetic basis of the characteristic “short stature” in Solanum lycopersicum L.; conducting an individual selection from sporophyte variety populations; testing selected samples in a multi-tiered narrow-rack hydroponics installation; selecting the most large-fruited and productive samples; transferring new varieties to the State Variety Testing (GSI), and analyzing the economic efficiency of cultivating new varieties on multi-tiered hydroponic installation. As a result, in the Federal Scientific Center for Vegetable Growing, the first varieties of tomato vertical vegetables such as “Natasha” (Patent of the Russian Federation No. 9060) and “Timosha” (Patent of the Russian Federation No. 9059) were obtained. Our analysis of the economic efficiency of tomato cultivation on multi-tiered narrow-rack hydroponics demonstrated the convincing advantages of such a method of tomato cultivation as compared to the traditional cultivation method.

1. Introduction
Vertical vegetable growing is an innovative direction in the technological development of protected ground. Its relevance is due to the need to save energy, nutrient substrate and water in conditions of the growing world population and the growing urban space. The so-called “urban farms” means growing plants in vacant areas in an urban environment, for example, in underground boxes, on rooftops, in closed greenhouses. At the same time, less space is used, and the consumption of energy and water is significantly reduced, which distinguishes these technologies from traditional farming methods [1]. In 2015, the volume of the vertical vegetable market amounted to 1.15 billion dollars. By the end of 2016, a 25% growth was observed, and an increase in the market volume to 6.0 billion dollars is expected by 2025 [2]. The main market segment (42%) is occupied by the countries of the Asia-Pacific Region (China, India, Japan, Taiwan, Singapore, South Korea), in which the shortage of acreage and water for irrigation is already felt. Then the countries of Europe (30%), namely United Kingdom, Germany,
France, Belgium, the Netherlands follow, and then the countries of North America (21%), namely Canada, the USA and Mexico follow. 7% of the market is occupied by other countries [3]. It should be noted that the main volume of the market are green crops and strawberries. The main vegetable crops of protected ground (tomato, cucumber, sweet pepper) are represented to a small extent [4]. The domestic market of vertical growing is in the process of formation.

Tomato ranks first in the world among vegetable crops on cultivated areas in open and protected ground, the area occupies 3.7 million hectares with a yield of 45-65 t / ha. The People's Republic of China holds the lead in the areas occupied by the tomato crop, the area is 974 thousand hectares. The annual production of fresh tomatoes in China is 25 million tons. The Russian Federation ranks sixth in terms of the area under this crop (142 thousand hectares) and occupies 11th place in the production of fresh tomatoes per year (1.82 million tons) [5]. Therefore, we chose the cultivation of tomato for our analysis, focusing on the technology of vertical vegetable growing. In the State Register of Breeding Achievements Being Approved for Use in 2011, 1,630 registered samples (varieties and hybrids) of tomato were found [6]. But among them there was not a single dwarf variety / hybrid that, according to morphological characteristics (a plant height of 35-50 cm), would be suitable for growing on multi-tiered hydroponic plants.

The purpose of the study is to analyze the dwarf tomato varieties adapted for cultivation on multi-tiered hydroponic plants, according to the technology of vertical vegetable farming.

Research objectives: (1) creating a variety / hybrid model for multi-tiered narrow-rack hydroponics; (2) analyzing the genetic basis of short stature in tomato according to the literature; (3) selecting undersized samples from the collection of varietal populations of the laboratory of new technologies using sporophyte selection; (4) testing the selected tomato samples on a multi-stage narrow-rack hydroponics installation and selecting the most productive samples; (5) analyzing the economic efficiency of cultivation of new tomato varieties intended for multi-tiered hydroponic plants.

2. Materials and Methods
The research material was the following collections of tomato *Solanum lycopersicum* L., collected by the employees of the Laboratory of New Technologies of the Federal Scientific Center for Vegetable Growing in different years of research:

- Collection from the Kazakh Research Institute of Potato and Vegetable Production (Kainar village, Alma-Atinskaya region) – 48 samples;
- Collection from the Ukrainian Institute of Vegetable and Melon-Growing of the Ukrainian Academy of Agrarian Sciences (UAAS) (Kharkiv) – 42 samples;
- Collection of tomato marker mutants from the Institute of Ecological Genetics of the Academy of Sciences of Moldova (Kishinev) – 518 samples;
- Collection of the West Siberian Experimental Station of the All-Russian Research Institute for Vegetable Growing (Moscow Region) – 27 samples;
- Collection of samples of tomato from the Republic of Sri Lanka – 57 samples.

A total of 692 tomato samples from the above collections were examined. In addition, samples of the *F*₂ – *F*₇ generations, isolated from the variety populations in the selection process, were studied. Our research methods included: (1) creating a model of a new form of tomato for the multi-tiered narrow-rack hydroponics; (2) an analytical review of the literature on the genetic basis of dwarf tomatoes; (3) an individual sampling from varieties of sporophytes in the rassadnom branch of a greenhouse with a polycarbonate coating type of the Richelle French company.

Seedlings were grown in standard cassettes / blocks of a mineral wool in the seedling compartment of the greenhouse. As the root environment, peat nutrient substrate / blocks of mineral wool were used. Tomato seeds, pre-treated with a 0.1% *KMnO₄* solution, were sown in peat-filled cartridges / corks for mineral wool blocks. With adventing the 5th true leaf, the plants were planted in the pots / blocks of a mineral wool and placed on tables in the seedling section of the greenhouse. When growing seedlings, a previously developed nutrient solution was used [7].

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With the advent of buds, the plants were set up on a multi-tiered narrow-rack hydroponics unit. First, testing the selected low-growing specimens on the installation of a five-tier narrow-rack hydroponic takes place. The design of such five-tiered narrow-rack hydroponics is a truncated pyramid with a base of 900 cm x 200 cm and a height of 250 cm. Trays from the stainless steel settle down on the iron basis in 5 tiers. Above trays are closed by a cover from the same material with holes for installation of pots with plants. The tray depth is 10 cm, its width is 15 cm. The site of automated solution supply through the pipes of “FITO” NPO is located at the end of the pyramid. The feeding of the nutrient solution into the trays is done automatically, the reverse flow of the solution is performed by gravity. The plants were grown either in 0.5 l pots filled with peat: perlite (1: 1), or in blocks of a mineral wool. The density of installation of plants on the structure of the MUG is 5 plants per 1 meter. The feeding mode of the nutrient solution is as follows: the feeding time is 5-10 minutes with an interval of 40 minutes. For growing the adult plants, a nutrient solution was used, which was also developed earlier [7]. The light sources were the lamps “DNа3-400” (“Reflaks” LLC). When growing tomato plants, the air temperature was + 22 / + 24 °C during the day and + 18 / + 20 °C at night; the relative air humidity within 50-60% was maintained. The duration of the light period is 16 hours / day. Second, we also relied in biometric measurements. The productivity of plants and the fetus mass was determined by the gravimetric method. Third, the dispersion analysis of research results was performed according to [8].

3. Research results

3.1 Creating a model of a new form of tomato for multi-tiered narrow-rack hydroponics

It was carried out on the basis of classical works on the genetics and biology of tomato [9-11], as well as on the basis of our own experimental data [12], [13].

| Feature | Small-fruited variety | Medium-fruited variety |
|---------|-----------------------|------------------------|
| 1 Dwarfism - plant height | 30-35 cm | Dwarf - superdet – plant height | 45-50 cm |
| 2 Productivity | 450-500 g / plant | Productivity | 850-1,000 g / plant |
| 3 Maturation term (shoots - ripe fruit) | 78-82 days | Maturation term (shoots - ripe fruit) | 78-82 days |
| 4 Brush | Difficult compact | Brush | Simple elongated, intermediate |
| 5 Laying brush | After the second true leaf | Laying brush | After the second and third true leaf |
| 6 Stem | Thick, dense | Stem | Thick, dense, popping after 4-5 inflorescences |
| 7 Forming Leaf | 2-3 stalks | Forming | Without forming |
| 8 Leaf | Smooth / slightly corrugated, horizontal / hanging | Leaf | Smooth / slightly corrugated, horizontal / hanging |
| 9 Mass of 1 fruit | 10 - 25 g | Mass of 1 fruit | 35-55 g |
| A number of fruits on the plant | 20-35 pieces | The number of fruits on the plant | 25-35 pieces |
| 10 Tolerance | To low light, to abiotic and biotic stresses | Tolerance | To low light, to abiotic and biotic stresses |

3.2 Analysis of the genetic basis of short stature in tomato

The sign “short stature” in tomato is controlled by a group of \( d \)-genes, which are localized in the long arm of chromosome 2, control the biosynthesis of brassinosteroids, and are represented by 11 alleles [14], [15]. The degree of expression of a characteristic depends on environmental conditions [16]. A selectively useful property associated with the \( d \)-genes is their manifestation in the early stages of plant
development, namely, before flowering. Given the heterphase alternation of generations in higher plants, which implies the existence of asexual generation – diplophase (sporophyte), originating from zygotes before the onset of meiosis in sporocytes, and the sexual generation – haplophase (gametophyte) [17], the individual selection of stunted plants from populations can be conducted by sporophyte in the seedling compartment of the greenhouse. In addition, it is known that the d-genes are localized on chromosome 2 next to the genes controlling early maturity [10], [14]. With clutches, they can be inherited at the same time.

3.3 Selecting short-growing and early-ripe samples from the collection of varietal populations of the laboratory of new technologies using sporophyte selection

Taking advantage of the expression of the d-genes, we conducted a selection for the sporophyte in the seedling compartment of the greenhouse. A total of 8 short and early maturing individuals from 692 collection samples of tomato were selected. Their productivity parameters were further studied on a five-tier hydroponic installation. Thus, we managed to speed up the selection process 3 times. The results of our studies, processed statistically, are presented in Table 2. The principle of sporophyte selection is shown using 10 samples from each collection.

Table 2. Analysis of plant height and sporophyte selection in the short and early ripening tomato individuals for multi-tiered hydroponic plants. Greenhouse “Richelle” FSBI VNIISSOK. I and II turnovers, 2012.

| No. | Sample | Plant height, cm | The period of “shoots-maturation”, day | Sample | Plant height, cm | The period of “shoots-maturation”, day |
|-----|--------|------------------|--------------------------------------|--------|------------------|--------------------------------------|
|     |        | 1    | 2    | 3    | 4    | 1    | 2    | 3    | 4    |
| I turn | Funtik | Tomato Marker Mutant Collection | West Siberian Experiment Station Collection |
| 1   | Mo 331 | 68   | -22  | 111  | -1  | 1C  | 75   | -29  | 96   | +14 |
| 2   | Mo 411 | 91   | -45  | 106  | +4  | 2C  | 52   | +8   | 94   | +16 |
| 3   | Mo 504 | 70   | -24  | 122  | -12 | 3C  | 42   | +4   | 103  | +7  |
| 4   | Mo 579 | 82   | -36  | 118  | -8  | 4C  | 73   | -27  | 95   | +15 |
| 5   | Mo 609 | 93   | -47  | 123  | -13 | 5C  | 51   | +5   | 87   | +23 |
| 6   | Mo 663 | 58   | -12  | 102  | +8  | 6C  | 82   | -36  | 98   | +12 |
| 7   | Mo 753 | 90   | -44  | 123  | -13 | 11C | 36   | +10  | 105  | +5  |
| 8   | Mo 782 | 88   | -42  | 123  | -13 | 41K | 77   | -31  | 109  | +1  |
| 9   | Mo 825 | 41   | +5   | 123  | -13 | 4K  | 33   | +13  | 103  | +7  |
| 10  | Mo 940 | 94   | -48  | 119  | -9  | 5K  | 30   | +16  | 91   | +19 |
|     |        | HCP₅₅ | 16  | HCP₅₅ | 7  |      | HCP₅₅ | 16  | HCP₅₅ | 7  |
| II turn | Funtik | Collection of the Republic of Sri Lanka | Collection from the Kazakh Research Institute of Potato and Vegetable Production |
| 1   | 31Π    | 116  | -78  | 93   | +17 | 36A | 90   | -52  | 105  | +7  |
| 2   | 32Π    | 104  | -66  | 96   | +14 | 37A | 110  | -72  | 94   | +16 |
| 3   | 33Π    | 98   | -60  | 98   | +12 | 38A | 112  | -74  | 101  | +9  |
| 4   | 34Π    | 118  | -80  | 107  | +3  | 39A | 136  | -98  | 107  | +3  |
| 5   | 35Π    | 130  | -92  | 105  | +5  | 40A | 108  | -70  | 107  | +3  |
| 6   | 36Π    | 72   | -34  | 94   | +16 | 41A | 126  | -88  | 92   | +18 |
| 7   | 37Π    | 86   | -48  | 100  | +10 | 42A | 106  | -68  | 96   | +14 |
| 8   | 38Π    | 70   | -32  | 105  | +5  | 43A | 72   | -34  | 100  | +10 |
| 9   | 39Π    | 108  | -70  | 107  | +3  | 44A | 70   | -32  | 105  | +5  |
| 10  | 40Π    | 90   | -52  | 113  | -3  | 45A | 108  | -70  | 107  | +3  |
|     |        | HCP₅₅ | 20  | HCP₅₅ | 13 |      | HCP₅₅ | 20  | HCP₅₅ | 13 |
Samples from the collection of the Ukrainian Institute of Vegetable and Melon-Growing of the Ukrainian Academy of Agrarian Sciences (UAAS) (Kharkiv, Ukraine) were already very tall at the seedling stage; therefore, none of them were selected for subsequent breeding. Samples from the collections of the Republic of Sri Lanka and the Kazakh Research Institute of Potato and Vegetable Production were also all tall, although a number of samples from these collections subsequently showed early maturity.

But the key feature that determines the possibility of cultivation on multi-tiered hydroponic plants is a short stature controlled by the group of d-genes. Therefore, when selecting for a sporophyte, we preferred this particular feature. The most productive was the selection from the collection of the West Siberian Experimental Station of the All-Russian Research Institute for Vegetable Growing. A total of 6 samples from 27 showed a short stature and early ripeness. The samples Mo663 and Mo825 were selected from the collection of tomato marker mutants of the Institute of Ecological Genetics of the Academy of Sciences of Moldova. The selection of these samples is of great value also because their genome is guaranteed to contain a group of d-genes. Summarizing the analytical studies of the height of plants by the sporophyte, we conclude that selection, by the sporophyte, at an early stage of plant development, could significantly (86 times) reduce the amount of material needed for further breeding work. As a result, 8 out of 692 samples were taken. This made it possible to more fully analyze the selected valuable material in a multi-tiered hydroponic installation.

3.4 Testing the selected dwarf samples on the installation of a five-tier narrow-rack hydroponics.

The installation of a five-tier narrow-tier hydroponic was installed in the “Richelle” greenhouse at the VNIISSOK in June 2013. The site of automated solution supply was kindly provided by the firm “FITO” NPO. We carried out the first round of studies on the productivity of the selected plants in the seedling section of the greenhouse in 2012. In subsequent years, all experiments were carried out on the installation of a five-tier narrow-rack hydroponics. In 2014, experiments were carried out in the first and second turns, in 2015 were in the first, second, and third turns. The experimental results, processed statistically, are presented in Table 3.

Table 3. Analyzing the productivity and average weight of the fetus in low-growing tomato samples, previously selected for sporophyte. Selection of productive samples. Greenhouse “Richelle” VNIISSOK. 2012-2015.

| No. | Sample   | 2012 (F₁) | 2014(F₂–F₃) | 2015(F₄–F₅) | Average weight of 1 fruit, g |
|-----|----------|-----------|-------------|-------------|-----------------------------|
|     |          | 2012(F₁)  | 2014(F₂–F₃)| 2015(F₄–F₅)| 2012(F₁)  | 2014(F₂–F₃)| 2015(F₄–F₅)|          |          |          |          |          |          |          |          |
| 1   | Fun tik - St | 221       | 187         | 199         | 53          | 7.4          | 8.5          |          |          |          |          |          |          |          |
| 2   | Mo 663   | 187       | 185         | -           | 55          | 48.0         | -            |          |          |          |          |          |          |          |
| 3   | Mo 825   | 213       | 178         | -           | 25          | 23.0         | -            |          |          |          |          |          |          |          |
| 4   | 2C       | 310       | 180         | -           | 28          | 20.0         | -            |          |          |          |          |          |          |          |
| 5   | 3C       | 249       | 173         | -           | 11          | 8.0          | -            |          |          |          |          |          |          |          |
| 6   | 5C       | 303       | 215         | -           | 20          | 18.0         | -            |          |          |          |          |          |          |          |
| 7   | 11C      | 304       | 206         | -           | 12          | 11.0         | -            |          |          |          |          |          |          |          |
| 8   | 4K       | 431       | 383         | 454         | 11          | 10.8         | 10.7         |          |          |          |          |          |          |          |
| 9   | 5K       | 358       | 369         | 501         | 10          | 10.0         | 10.3         |          |          |          |          |          |          |          |
| HCP₉ₙ | 129     | 54        | 68          | 16          | 2.2         | 1.8          |             |          |          |          |          |          |          |          |

It is quite difficult to select from the varieties of a self-pollinator, such as *Solanum lycopersicum* L., because these varieties are more or less homogeneous. However, by productivity, we were removed to select 2 small-fruited specimens with red and yellow fruits. In 2015, these samples were transferred to the State Commission of the Russian Federation for Testing Varieties. In 2017, two patents were obtained for them, particularly for the tomato varieties “Natasha” (red-fruited) and “Timosha” (yellow-fruited). These are the first tomato varieties that were created at the Federal Scientific Center for Vegetable Growing specifically for multi-tiered hydroponic plants using sporophyte selection technologies.
3.5 Analyzing the economic efficiency of new tomato varieties

The creation of tomato varieties for multi-tiered hydroponic plants allowed us to analyze the economic efficiency of the technology of vertical vegetable growing, especially in comparison with the traditional technology of cultivation of tomato culture in film greenhouses. The results are presented in Table 4. Such an analysis clearly shows the advantages of vertical vegetable production systems over traditional tomato cultivation technologies.

Table 4. Analyzing the economic efficiency of the vertical vegetable growing technology, in comparison with the traditional growing tomato technology in film greenhouses.

| Indicators                | Traditional technology | Five tier narrow-rack hydroponics |
|---------------------------|------------------------|----------------------------------|
| Number of crop turns      | 1-2 ordinary / 1 extended | 4 turns: I turn – 19.01-9.05     |
|                           |                        | II turn – 27.03-28.07            |
|                           |                        | III turn – 16.06-28.09           |
|                           |                        | IV turn – 16.08-14.12            |
| Productivity, kg / m²     | 45-55                  | 93-128                           |
| Selling price, rubles     | 70-71                  | 70-71                            |
| Costs, rub / m²           | 2,520                  | 2,532                            |
| Revenue, rub / m²         | 2,864                  | 8,145                            |
| Estimated profit, rub / m²| 344                    | 5,613                            |
| Profitability, %          | 25                     | 222                              |

4. Discussion

By 2050, approximately 85% of the 9 billion people on Earth will live in cities. More than that, food and water shortages will threaten a growing world population [1]. The problem solution is seen in the creation of the so-called “urban farms,” for which the vertical vegetable farming technologies are very relevant. They are already being developed and used by the leading countries of the world. Moreover, in the industrial district of Khabarovsk (Russia), the Japanese company “Mirai” built an agricultural complex equipped with modern hydroponic complexes. The peculiarity is the prohibition of using plant materials modified with microorganisms and chemical methods of pest control. With the commissioning of this complex, the region will be able to increase its self-sufficiency in vegetables and herbs from 10 to 60% [18].

In order to promote the technology of vertical vegetable growing in the protected soil of the Russian Federation, the project “Creating dwarf tomato varieties for high-bay hydroponic plants” started in VNIISSOK in 2011. Tomato is the leading open and protected ground vegetable crop in the world. However, the State Register of Breeding Achievements approved for use in the Russian Federation did not contain tomato varieties and hybrids that would meet the requirements for cultivation on high-bay hydroponic plants. We had to create these varieties “from scratch”. Ancestral forms of tomato *Solanum lycopersicum* L. are tall [9], [11].

Among the cultivated varieties of tomato, there are indeterminate and determinate forms, as well as ordinary and standard forms by habitus type [19]. We could not find any dwarf forms among them. Therefore, we began our scientific search by creating a model of a such tomato shape that would be adapted for multi-tiered hydroponic plants [7]. The key characteristic of this model is dwarfism. And dwarfism in tomato is controlled by a group of mutant *d*-genes [9].

In connection with this, we began to select the necessary forms for us in the collection of tomato marker mutants, which was maintained for a long period in the VNIISSOK Laboratory of Gamet Selection. The expression level of a group of *d*-genes depends on environmental conditions, but under favorable conditions, the sign of “short stature” manifests itself in the early stages of plant development [14], which allows selection by sporophyte [20]. Our pre-breeding selection was built on this technology, which made it possible to significantly reduce the volume of the studied material before conducting basic research on the installation of a five-tier narrow-rack hydroponics. The technology...
was named “target breeding” and was recognized internationally [21], [22]. Using this technology in pre-breeding, we created the tomato varieties “Natasha” and “Timosha,” designed specifically for multi-tiered hydroponic plants in the vertical vegetable production system. In 2017, VNIISSOK received their patents. Obtaining varieties for hydroponic plants allowed us to analyze the economic efficiency of the technology of vertical vegetable growing, which convincingly demonstrated the advantages of innovative technology of vertical vegetable growing compared with the traditional technology of growing in film greenhouses.

5. Conclusion

The innovative technology of vertical vegetable growing is the technology of the future. It requires a different approach to the selection process, when the selection process itself is considered as a technology for obtaining new plant forms, which includes several stages: (1) creating a model of a plant’s future shape; (2) pre-selection (pre-breeding); (3) defining the breeding strategy; (4) selection process; (5) testing new plant forms in various technological and ecological environments; (6) seed production of new plant forms.

This technology should be not only efficient, but also economically beneficial, i.e. at each stage, it should also include an economic component. It is known that the selection process is long and difficult. And the reducing volume of the studied material is most advantageous to carry out in the early stages of the study, in pre-breeding, which allows to significantly reduce the time to obtain new forms, and at the same time to give the most complete description of their productivity and adaptability in further production tests. For this, the key parameter is always useful to highlight which should be sought during the breeding work. The remaining parameters willfully or unwittingly correlate with this “key”. This principle, formulated by us as the principle of “target breeding” [22], allowed us to create (from a scratch) a number of new tomato varieties for contemporary technologies of vertical vegetable farming in a relatively short time.

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