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METHODS OF REGULATING THE GROWTH OF APPLE TREES IN INTENSIVE ORCHARDS

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Проаналізовано наукові літературні джерела щодо впливу підщеп, обрізування, підрізування, кільцювання, відгинання пагонів, застосування ретардантів і контрольованого дефіциту вологи на морфогенез та продуктивність яблуні. Виявлено, що найкращі результати дає поєднання агротехнічних і хімічних прийомів. Підщепи М.9, G.41 формують компактні дерева й забезпечують раннє плодоношення. Механічні методи (підрізування коренів, кільцювання, відгинання пагонів) зменшують приріст на 20–40 % і стимулюють закладання генеративних бруньок. Ретарданти (прогексадіон кальцію, паклобутразол) та контрольований дефіцит вологи (70–85 % ETc) обмежують ріст без втрати врожайності, покращують якість плодів і водозбереження. Найефективнішим методом є поєднання слаборослих підщеп, ретардантів, механічних прийомів і дефіциту вологи, що забезпечує баланс росту та плодоношення.

Ключові слова: *яблуня, інтенсивні насадження, регулювання росту, слаборослі підщепи, ретарданти, підрізування коренів, кільцювання, регульований дефіцит вологи, обрізування крони.*

State of the problem. Modern horticulture is focused on intensive technologies with a tree planting density of 2,500–4,000 trees/ha, in which low-growing rootstocks ensure early fruiting of trees and the possibility of forming compact crowns [1, 2]. Excessive vegetative growth causes shading of parts of the crown, a decrease in fruit quality (reduced size, lack of colouring and reduced taste) and increased costs for pruning and protection [3]. Growth regulation is based on physiological principles: maintaining an optimal balance between vegetative and generative plant development, optimising photosynthesis by improving light transmission [4]. The combined use of methods such as chemical regulators (retardants) and mechanical interventions allows for a significant increase in crop yield without reducing fruit quality [5].

Research objective. To analyse and summarise modern agrotechnical and chemical methods of regulating the vegetative growth of apple trees in intensive plantations in order to maintain an optimal balance between growth and fruiting, optimise photosynthesis by improving light transmission, and increase the overall efficiency of horticulture, yield, and fruit quality.

Research methodology. The review is based on an analysis of contemporary scientific literature. Data comparison and systematisation methods were used for generalisation, which made it possible to identify the main trends and approaches to regulating apple tree growth depending on agricultural techniques.

Results of the research. The main methods of growth regulation include:

Dwarf rootstocks are the basis of intensive plantings, as they allow for increased planting density and a 40–60% reduction in tree height compared to plantings on seed rootstocks, promoting early fruiting (in the 2nd–3rd year) [6]. For vigorous varieties such as "Honeycrisp" and "Fuji", clones M.9 (T337, Pajam2), PB.9 and G.41 are recommended, while for less vigorous varieties such as "Gala" and "Champion", M.26 or G.202 are optimal [7].

Slow-growing rootstocks reduce the growth of the trunk diameter by 25–45% and vegetative shoots, which improves the light transmission of the crown, promotes more uniform development of the overgrown wood and increases yield [8]. In high-density plantings (2500–3000 trees/ha) using the M.9 rootstock, plants can be planted at a distance of 0.7–1 m in a row [9]. Studies have shown that the M.9 rootstock reduces growth by 30% without yield loss, but requires well-drained soils to prevent root rot [10]. Slow-growing rootstocks also interact with other agronomic methods of growth regulation. The combination of low-growing rootstocks with retardants allows for additional limitation of vegetative shoot growth, improving light penetration into the crown and stimulating the process of generative bud formation, redirecting resources to fruit formation and increasing yield [6]. Modern genetically modified lines, such as MdWRKY9, enhance the weak growth effect of rootstocks, allowing for denser planting of up to 3,500 trees/ha with a yield of up to 120 t/ha and increasing the trees' resistance to high temperatures, drought and pests [11, 12]. This combination of technologies allows for an optimal balance between growth and fruiting, increasing the efficiency of intensive orchards and product quality.

Root pruning is one of the agrotechnical methods of regulating the growth of apple trees, which is used to reduce vegetative growth, stimulate fruiting and improve fruit quality. This method involves mechanical pruning of roots at a depth of 40-50 cm at a distance of 0.4–0.5 m from the trunk [13], which limits the absorption of water and nutrients, affecting the hormonal balance of the plant [14]. Root pruning partially disrupts the transport of auxins to the upper part of the tree, which contributes to the redirection of resources to generative processes [15, 16].

Studies show that root pruning during dormancy (winter) or at the beginning of vegetation (early spring) ultimately reduces growth by 26–30% compared to the control, which contributes to the formation of a compact crown [17]. For example, in studies of McIntosh and Muts apple orchards, root pruning reduced the concentration of gibberellins (GA1, GA4) in shoots by 20–30%, which led to a reduction in their length by 15–25% [18]. At the same time, the level of abscisic acid (ABA) increased, which contributed to bud differentiation and starch accumulation in the above-ground part of the crown [19]. In Granny Smith and Jonagold varieties, root pruning reduced the length of annual growth by 12–18 cm and increased the number of flower buds by 25–35% [14], increasing yield by 10–20% due to better distribution of nutrients, although in the first year after the procedure, a temporary decrease in yield by 5–10% is possible due to stress [20].

However, root pruning has certain risks. Excessive restriction of the root system (more than 30% of root mass) can weaken the tree and reduce its resistance to drought and disease [21]. For varieties on low-growing rootstocks, such as M.9, the method should be used with caution due to the limited root system [22]. It is recommended to prune every 2–3 years, alternating sides of the row to minimise stress and ensure stable yields. Combining root pruning with other growth regulation methods can enhance the effect [23].

Girdling involves removing a narrow strip of bark (usually 1–2 cm wide) around the trunk or branches of a tree. The purpose of the procedure is to prevent the phloem transport of nutrients, which leads to the accumulation of photoassimilates – carbohydrates, hormones and other metabolites – in the parts of the tree above the ringing site, while the organs below, in particular the roots, experience a deficiency of these substances [24, 25]. This agricultural practice is used to regulate vegetative growth, stimulate the formation of generative buds, increase yield and improve fruit quality, especially in intensive plantations [26]. Current research focuses on the physiological mechanisms of this agricultural practice, optimal parameters (time of implementation, width and location of the cut) and potential risks, such as tree weakening and stress.

The mechanism of action of girdling is to block the transport of nutrients in the plant, causing the roots to 'starve' due to a lack of carbohydrates [27]. This inhibits root system growth and directs resources to the reproductive organs. Studies show that soluble sugars and starch accumulate above the cut site, while their concentration decreases sharply below it. For example, in citrus crops, girdling causes a 2–3-fold increase in starch content in the leaves and bark above the cut site and a simultaneous decrease in the roots by 80–95% [28, 29]. In apple orchards, ringing is particularly effective for controlling the growth of shoots of vigorous varieties, promoting the formation of overgrown wood. At the same time, its effect on fruit size is less significant compared to other crops, such as peaches [24].

Bending shoots is a mechanical method of regulating apple tree growth used in intensive orchards to overcome apical dominance, stimulate lateral branching, improve crown structure and balance between vegetative and reproductive development [30, 31]. This technique involves mechanically changing the angle of shoots or branches relative to the vertical, usually to 40–60°, using tools such as clips, toothpicks, wire struts, ropes or supports. The procedure is performed on young shoots (10–15 cm long) or branches up to 20 mm in diameter to avoid breaking them. The fixation is removed after 2-3 weeks when the shoot is fixed in a new position [32, 33].

The effect is based on gravimorphism and auxin redistribution. A horizontal or inclined position inhibits vegetative growth, promotes the accumulation of carbohydrates for generative buds, and reduces apical dominance by redistributing growth energy to lateral shoots [34, 35]. Studies show that bending reduces shoot length by 15–30%, increases the number of fruit buds by 20–25% and increases crop yield by 10–15% compared to the control [36, 37].

This method is effective for forming spindle-shaped crowns, where branches are bent back for better light penetration (reducing the shaded area to <30%) and preventing the formation of sharp angles, which prevents them from splitting under the weight of the fruit [38]. Bending shoots is an effective agricultural measure, but it requires periodic adjustment [39, 40] and involves potential risks (branch brittleness, formation of fat deposits when the position is too horizontal, and a temporary decrease in photosynthesis due to stress) [41, 42].

Stem pruning is a mechanical method of regulating the vegetative growth of trees, used in intensive orchards to inhibit apical dominance, stimulate the differentiation of generative buds, and optimise the balance between vegetative and reproductive development [43, 44]. This agrotechnical technique involves making horizontal cuts on the tree trunk to a depth of approximately 1/3 of the trunk diameter, on two opposite sides, with a pitch of 20–30 cm. The agrotechnical measure is performed during the dormant period before the start of sap flow or during the period of active growth (after flowering), using chainsaws [45, 46].

The physiological mechanism of this agricultural measure is based on a partial disruption of phloem and xylem transport, which leads to the accumulation of carbohydrates and phytohormones (in particular, auxins and cytokinins) in the upper part of the tree above the incision site, reducing their polar transport [44, 47]. According to research results, this agricultural measure reduces the annual growth of shoots by 20–35%, increases the formation of fruit buds by 15–25% and increases the yield of apple trees by 10–20% compared to the control, especially in vigorous varieties [48, 49].

The effectiveness of the method depends on the depth of the cuts (no more than 1/3 of the stem diameter) and the number of cuts (on one or both sides), with mandatory post-treatment of wounds with fungicides to prevent pathogenic invasions, such as *Erwinia amylovora* or *Phytophthora spp*. [50, 51]. Compared to chemical growth regulators, trunk pruning is a more environmentally friendly and cost-effective agricultural practice, and its effect is prolonged (1–2 seasons) and requires integration with other elements of cultivation technology, such as pruning, chemical protection and balanced nutrition [52, 53]. Potential risks include a temporary decrease in photosynthetic activity and increased sensitivity to stress factors, which has been confirmed in damage simulation models [51].

Crown pruning is a fundamental agricultural practice in modern intensive horticulture, as it determines the architecture of the tree, optimises fruiting and controls vegetative growth. Proper crown formation ensures an optimal balance between leaf mass development and productivity, which directly affects the quantity and quality of fruit [55–57]. The choice of pruning time – winter or summer – plays a key role in achieving these goals [58, 59]. Winter pruning is traditionally used to lay the main skeletal branches and form the crown, while summer pruning (July–August) is more effective in limiting excessive shoot growth and improving fruit quality. In particular, summer pruning reduces the length of shoots and the development of subcutaneous bitter spots on the fruit, without negatively affecting their weight and taste [60].

The results of studies conducted in 2023 confirmed the benefits of summer pruning and its positive impact on yield. Pruning in August resulted in a 30–33% increase in yield compared to winter pruning in February [55]. This is explained by a moderate reduction in competition between vegetative and reproductive organs and a 15–20% decrease in tree growth without significant stress [61]. At the same time, excessive summer pruning, when more than 20% of shoots are removed, can reduce yield by 5–7% due to the loss of leaf surface area [62].

Biological risks must be taken into account when planning pruning. Pruning during or immediately after flowering is not recommended, as this increases the likelihood of infection with bacterial blight (*Erwinia amylovora*) [63]. Thus, summer pruning requires adapting the timing and methods to climatic conditions, variety and age of the tree. Winter pruning is best used for crown formation, while summer pruning is best used for growth control and fruit quality improvement. Combining these approaches allows for maintaining an optimal balance between vegetative and reproductive processes, ensuring stable and high-quality apple tree yields.

One effective way to control growth is to use retardants – chemical compounds that inhibit gibberellin biosynthesis. They limit cell elongation, reducing shoot growth, which optimises crown structure and increases photosynthetic efficiency. Among retardants, calcium prohexadione is the most common due to its high efficiency and low toxicity. Other compounds, such as paclobutrazol (PBZ), daminozide and uniconazole, are also used to control growth, but to a lesser extent. Calcium prohexadione effectively reduces shoot length without negatively affecting yield and fruit quality. For example, in studies on “d'Anjou” pear orchards, the application of calcium prohexadione at a dose of 250 mg/l reduced shoot length by 28–41%, shortening internodes and improving crop quality [64]. In plantations of the “Le Conte” pear variety, a dosage of 100–400 mg/l effectively controlled vegetative growth, although no effect on yield and fruit quality was established [65].

In apple orchards of the “WA 38” variety, treatment with calcium prohexadione (250 ppm after flowering) reduced internode length and total shoot length by 42%, while increasing transpiration, chlorophyll concentration in leaves and average fruit weight [66]. Combined application with ethephon in “Northern Spy” apple trees showed that calcium prohexadione significantly reduces growth length without affecting flowering intensity or yield, while ethephon stimulates flowering [67].

Paclobutrazol is a potent gibberellin inhibitor with a long-lasting effect. In apple and pear orchards, it reduces tree height, trunk diameter and shoot length by 34–57%, improving fruiting and fruit quality. In addition, there is a decrease in fruit acidity and an increase in calcium content [68]. Daminozide, historically used to control apple tree growth, in McIntosh orchards when applied up to 5 weeks after full bloom, improved the colour of the fruit skin, reduced pre-harvest fruit drop, increased pulp density, delayed starch hydrolysis and reduced ethylene production [69, 70].

In high-density apple orchards, retardants help optimise crown structure. Calcium prohexadione and paclobutrazol reduce vegetative growth, improve light penetration to all parts of the crown and effectively control bacterial burn. In pear orchards, retardants prevent excessive growth, increase the Ca and K content in fruits and improve yield [71]. For other fruit crops, such as cherries or citrus fruits, the use of retardants helps to accelerate fruit ripening and improves their storage.

Controlled deficit irrigation is an effective agronomic method for managing the vegetative growth of apple trees, especially in conditions of limited water resources. This approach involves deliberately limiting water supply at certain stages of plant development, which helps to reduce excessive shoot growth, optimise the distribution of water and nutrients to reproductive organs, and increase water use efficiency. Studies show that moisture deficit not only controls tree growth, but can also maintain or even improve fruit yield and quality without significant losses [72–74].

The application of this agricultural measure in apple orchards is particularly effective during the periods from flowering to fruit set. Moderate water restriction at 55–70% of crop evapotranspiration (ETc) optimises water use and improves fruit quality compared to full irrigation [75]. For example, a moderate deficit (85% ETc) in the early stages of development (from bud break to flowering and fruit setting) reduces the leaf area, which limits evapotranspiration and inhibits excessive shoot growth, promoting the redirection of resources to fruit development [76].

Deficit irrigation at 85% and 70% ETc significantly reduces shoot growth intensity, stem diameter and chlorophyll index compared to full irrigation, which is explained by the limitation of cell turgor and photosynthetic activity. Controlling growth in this way reduces competition between vegetative and generative organs, lowers pruning costs and promotes stable fruiting. At the same time, it can increase yield: at 85% ETc, there is an increase in productivity and water use efficiency [75]. However, severe deficits (40% ETc) should be avoided during fruit growth, as this can reduce yield by 20%.

Irrigation deficit also has a positive effect on fruit quality by stimulating the accumulation of bioactive compounds. In particular, the total phenolic content in fruits can increase to 5.95 mg/g of fresh weight at 70% ETc, and anthocyanins – to 7.54 mg/100 ml, which improves the antioxidant properties and colour intensity of fruits [77, 78]. In general, the use of this method allows increasing water use efficiency to 60% without crop losses. Mild water stress during fruit growth controls plant growth, preserving fruit size and quality. Controlled moisture deficit is a sustainable and effective method of reducing the growth rate of fruit trees, which contributes to water savings, increased yields and improved fruit quality. The effectiveness of this method depends on the precise selection of the irrigation restriction period and the level of deficit, with a particular focus on the early stages of fruit development [79].

Conclusions. Effective management of apple tree growth processes is a key condition for the stable functioning of intensive plantations aimed at obtaining high-quality products at optimal resource costs. Growth regulation should be based on a comprehensive approach that takes into account the biological characteristics of the variety, rootstock, technological system of orchard maintenance, and environmental conditions of cultivation. The most effective strategies are those that combine the use of low-growing rootstocks, mechanical techniques, and physiological methods. Such comprehensive measures not only curb excessive vegetative growth, but also stimulate the formation of generative buds, ensuring better illumination of the inner part of the crown, increasing the efficiency of the photosynthetic apparatus and the quality of the fruit. Recent studies show that controlled moisture deficit (70–85% ETc) and calcium prohexadione act as growth inhibitors, reducing shoot elongation without reducing yield. Mechanical methods, in particular root pruning and girdling, provide a long-lasting growth regulation effect by redistributing carbohydrates and phytohormones in the root-shoot system.

Thus, a rational combination of agrotechnical and physiological techniques creates an optimal balance between the vegetative and generative development of apple trees, increases the resistance of plantings to stress factors, and ensures a stable harvest. The use of a growth regulation system as part of integrated orchard management is a promising direction for the development of modern fruit growing, which is in line with the principles of environmental sustainability and resource conservation.

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Annotation

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Methods of regulating the growth of apple trees in intensive orchards

Objective. To summarise current scientific approaches to regulating the vegetative growth of apple trees in intensive plantations and to evaluate the effectiveness of mechanical, physiological and chemical methods of influencing growth and fruiting. Methods. An analytical review of scientific sources (2015–2025) was conducted, which examined influence of rootstocks, crown pruning, root and trunk pruning, ringing, shoot bending, the use of retardants and controlled moisture deficiency on morphogenesis, photosynthetic activity, phytohormone balance, and apple tree productivity. Comparative, systematic, and physiological-analytical methods were used to integrate the data obtained. Results. It was found that optimal growth regulation is based on a combination of agrotechnical and chemical methods. Weak-growing rootstocks M.9, G.41 and their analogues ensure compact trees and early fruiting, while mechanical methods (pruning roots and trunks, ringing, bending shoots) reduce growth by 20–40% and stimulate the formation of generative buds. Chemical growth regulators (calcium prohexadione, paclobutrazol) limit shoot elongation without reducing yield, and controlled moisture deficit (70–85% ETc) further increases water use efficiency and fruit quality.

The combined use of methods allows achieving a balanced ratio between vegetative and generative development, improving crown illumination and reducing the labour intensity of pruning. Conclusions. Effective regulation of apple tree growth in intensive plantings is achieved through the integration of biological, mechanical and physiological factors. The most effective combination is slow-growing rootstocks with retardants and mechanical techniques (root pruning, shoot bending). The use of controlled moisture deficit not only inhibits vegetative growth but also improves fruit quality and the water-saving potential of the orchard. The generalisations obtained are of practical importance for the development of adaptive apple cultivation technologies in the context of climate change.

Key words: *apple tree, intensive plantings, growth regulation, low-growing rootstocks, retardants, root pruning, ringing, controlled deficit irrigation, crown pruning.*