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# The impact of innovative queen cages on queen quality and colony strength in profitable beekeeping enterprises in the United States

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***Abstract.*** *The relevance of the study stems from the urgent need to improve queen bee transportation methods within the commercial beekeeping industry of the United States, where high production rates, geographic mobility, and the demand for colony stability require technologically advanced cage designs. The continued use of outdated or non-adaptive cages leads to reduced queen productivity, delays in colony integration, and increased losses, all of which negatively affect the profitability of beekeeping operations.*

*The* ***purpose*** *of this study is to determine how modern engineering innovations in queen cage design influence key biological indicators that ensure the formation of strong and productive colonies.*

*The* ***research methodology*** *is based on a synthesis of findings from publicly available field studies and literature sources, with a focus on assessing the effectiveness of different cage types. The study includes engineering analysis of cage structures and generalization of data regarding queen survival rates, time to* *oviposition, brood quantity, and colony strength at the onset of the productive period.*

*The **results** indicate that next-generation cages with built-in feeding reservoirs and escort bee microchambers significantly outperform traditional designs. Survival rates increased to 96–97%, compared to a maximum of 85% in older cage models. Queens placed in innovative cages began oviposition 1.5 to 2 days earlier, and the number of open brood cells observed 10 days post-introduction was 25–30% higher. These cages also contributed to more stable colony formation and lower queen loss during transportation. Notably, these effects were consistent across both medium and large commercial beekeeping operations.*

***Conclusions.** The findings confirm that the implementation of advanced cage designs minimizes stress, improves queen acceptance rates, and ensures the rapid development of strong colonies—an essential factor for profitability in modern beekeeping. Future research should focus on developing standardized industrial cage models suitable for integration with automated transportation and monitoring systems, as well as assessing their performance under varying regional and climatic conditions across the United States.*

***Keywords:** cage design, queen survival, colony integration, queen adaptation, commercial apiculture, transport efficiency.*

## Вплив інноваційних кліточок на якість маток і силу бджолосімей у рентабельних пасічних господарствах США

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***Анотація.*** *Актуальність дослідження зумовлена необхідністю вдосконалення засобів транспортування бджолиних маток у системі комерційного бджільництва США, де високі темпи виробництва, мобільність господарств і вимоги до стабільності бджолосімей вимагають використання технологічно ефективних конструкцій кліточок. Застосування неадаптованих або застарілих моделей спричиняє зниження продуктивності бджолосімей, зростання втрат і, як наслідок, негативно впливає на рентабельність пасічного виробництва.*

***Метою*** *статті є встановлення впливу сучасних інженерних рішень у конструкціях кліточок для перевезення маток на основні біологічні показники, що визначають формування сильних і продуктивних бджолосімей.*

***Методологія*** *роботи базується на узагальненні доступних джерел і результатів польових досліджень, описаних у сучасній літературі, з метою оцінювання ефективності різних типів кліточок. Проаналізовано інженерні характеристики конструкцій, а також підбито підсумки про дані щодо рівня виживаності маток, часу початку яйцекладки, кількості відкритого розплоду та сили бджолосімей на старті продуктивного періоду.*

***Результати*** *дослідження засвідчили, що кліточки нового покоління, оснащені кормовими резервуарами та мікрокамерами для супровідних бджіл, демонструють значно кращі показники порівняно зі стандартними зразками. Зокрема, середній рівень виживаності маток зріс до 96–97%, тоді як у традиційних конструкціях він не перевищував 85%. Час до початку яйцекладки скоротився в середньому на 1,5–2 доби, а кількість відкритого розплоду за перші 10 днів після підсадки була вищою на 25–30%. Також зафіксовано більш стабільне формування повноцінної бджолосім'ї та зниження рівня втрат маток у процесі транспортування. Позитивні результати спостерігались як у середніх, так і у великих пасічних господарствах із різним рівнем механізації процесів.*

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***Висновки.*** *Встановлено, що використання вдосконалених кліточок дає змогу значно зменшити вплив стресових чинників, підвищити ефективність підсадки маток та забезпечити стабільний розвиток бджолосімей, що є ключовим чинником рентабельності у сфері сучасного комерційного бджільництва. Перспективи подальших досліджень охоплюють розроблення стандартизованих інженерних рішень для масового виробництва кліточок, адаптованих до автоматизованих систем логістики й моніторингу, а також проведення регіональних випробувань у різних кліматичних умовах США.*

***Ключові слова:*** *конструкції кліточок, виживаність маток, прийняття у сім'ї, адаптація бджолиних маток, комерційне бджільництво, ефективність транспортування.*

**Problem Statement.** Under current conditions of intensive beekeeping in the United States, there is a growing need to improve technologies for transporting and housing queen bees, as these directly affect colony productivity and viability. The use of innovative queen cages for transport is seen as a promising approach to enhance post-shipment adaptation, reduce mortality, and increase acceptance rates within recipient colonies. However, existing cage designs do not always align with the biological needs of queens and attendant workers, which can compromise the queens' reproductive potential and reduce the overall profitability of commercial beekeeping operations.

The core issue lies in the insufficient scientific validation of the relationship between the technical characteristics of queen cages and key indicators of queen quality and colony strength. In the context of U.S. commercial beekeeping – where not only the safe transport of the queen but also her successful integration into a productive colony is essential – there is a pressing need to evaluate the effectiveness of various cage types, taking into account bioengineering, logistical, and economic factors. This highlights the importance of developing new cage models that ensure consistent queen acceptance, preservation of reproductive capacity, and strengthening of colonies, which is critical both for research advancement and for the practical success of modern commercial beekeeping.

**Analysis of recent research and publications.** The analysis of scientific papers that reveal the impact of innovative cages on the quality of queens and the strength of bee colonies in apiaries allows us to identify four main areas of research.

The first area covers the study of the relationship between the quality of queen bees, in particular their reproductive function, and external biotechnical or biological factors. The work of E. Amiri et al. emphasizes that bee diseases, in particular viral infections, can have a synergistic negative effect on the physiological quality of the queen, impairing its acceptance and reproductive activity [1]. The publication of N. Szawarski et al. demonstrated the effect of gibberellic acid on the quality of queen cells and the subsequent reproductive efficiency of queens in *Apis mellifera* colonies, which may be relevant when combined with innovative cage solutions [2]. Further research in this area should be focused on determining the interaction between cage design, the level of stress during transportation, and the physiological quality of the queen under different climatic and microbiological conditions.

The second area concerns the economic justification for introducing innovations in the rearing and transportation of queens in the United States and Canada. M. Bixby et al. analyzed the cost of queen production in Canada and the impact of the quality of the delivery process on overall profitability, pointing to the need to modernize cages to reduce losses [3]. L. A. Holmes et al. compared the performance of imported and local queens, emphasizing the importance of transportation conditions and the quality of cages for the survival and winter hardiness of bee colonies [4]. M. Vercelli and co-authors emphasize the need to adapt biotechnical measures to combat varroa with economic feasibility, where improved cages can be an element of sustainable management [5]. Further research in this area should be aimed at determining the relationship between the cost of innovative cages and the economic result from reducing losses, delays in uterine acceptance and increased productivity.

The third area reveals technologies of genetic selection and innovations in queen rearing, which are directly related to transportation efficiency. G. Gertje et al. proposed a model of genetic improvement programs in beekeeping, which includes controlled rearing and logistics of queen transportation, where improved cages are a prerequisite for realizing genetic potential [6]. S. Maucourt et al. demonstrated the growth of genetic progress through instrumental insemination, the effectiveness of which also depends on proper protection of the uterus during transportation [7]. L. Umiraliyeva et al. have shown that the use of wax cups for larval rearing helps to reduce stress and improve the quality of uterine material [8]. Further research should focus on the integration of cage engineering solutions with genetic control programs and the development of universal requirements for bioengineering transportation.

The fourth area includes issues of general management of bee farms, strategies for keeping bee colonies and market prospects for queen queen. R. M. Underwood et al. argue that organic apiary management is not inferior to conventional methods, and the design of cages should comply with the principles of organic production [9]. B. T. Nganso et al. emphasize the role of cages as an element of effective colony care in Africa [10]. O. Olshansky considers the prospects for the export of American queen bees, focusing on logistics and regulatory requirements for transportation methods [11]. O. Frunze et al. compare systems for preserving breeding resources, in particular in the context of choosing cages [12]. L. A. Holmes et al. demonstrate the effectiveness of re-planting queens into established colonies provided that the cages are selected correctly [13]. M. Vercelli and co-authors propose a tool for apiary accounting that takes into account the efficiency of queen use, taking into account the factor of acceptance through the cells [14]. R. Sharma et al. in a manual for beekeepers systematize recommendations for the selection and use of cages in modern beekeeping [15]. Further research should focus on the development of


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standards for beehives that cover the environmental, legal, and logistical requirements of the American market.

**Identification of previously unresolved parts of the overall problem.** Despite the existence of some studies on the design of cages for transporting queen bees, there are still a number of unresolved aspects that limit the practical effectiveness of their use. In particular, the correlation between the technical characteristics of the cages and the biological parameters of queens at the stage of post-transportation adaptation has not been sufficiently studied. The small amount of empirical data on the impact of specific engineering solutions on the survival, acceptance and reproductive activity of queens in large-scale commercial settings makes it difficult to formulate reasonable standards. Previous methodological approaches were mostly fragmented or did not sufficiently take into account the dynamics of queen development after queen integration.

The proposed work aims to overcome these gaps through a comprehensive analysis of cage designs from the standpoint of bioengineering compliance and impact on key indicators of family strength. Generalization of field observations and quantification of uterine parameters made it possible to establish patterns that have not been previously reported in the literature. Thus, the study forms the empirical basis for further standardization of cages and provides a new understanding of biologically adapted transportation as a critical stage in the system of profitable beekeeping.

**Formulation of the objectives of the article (statement of the task).** The purpose of the article is to determine the impact of innovative designs of cages for transportation of queen bees on the quality of queen bees and the strength of bee colonies in the context of increasing the profitability of US beekeeping farms.

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Objectives of the study:

1. To analyze the main types of cages for the transportation of queen bees in the United States in terms of technical characteristics and biological compliance, to characterize their advantages and limitations.

2. To evaluate and establish a correlation between the design of the cage (including feed tanks and microchambers) and the main biological parameters of queens - survival, integration rate, time to the start of oviposition and the strength of the formed bee colony.

3. To identify problems with the use of outdated cage models and develop practical recommendations for their optimization and standardization in the context of profitable commercial beekeeping in the United States.

**Summary of the main research material.** In the US commercial beekeeping system, transportation of queen bees is a critical stage that largely determines the effectiveness of further formation of productive bee families. Given the scale of beekeeping and the considerable geographical extent, producers are forced to use different types of cages adapted to logistical conditions, veterinary safety requirements, and the biological needs of the queen. The main goal of the design solutions is to create a safe environment that minimizes physiological stress, prevents injury or death of the uterus, and helps to preserve its pheromone activity. In the United States, both traditional wooden cages with ventilation holes and modern polymer structures with feed tanks are widespread, providing a better microclimate during transportation over long distances. The selection of the type of cage is based on the analysis of transportation conditions, delivery time, packing density, temperature conditions and requirements for accepting the queen upon arrival at the apiary (Table 1).

At the current stage of beekeeping development in the United States, leading farms are increasingly implementing innovative solutions in the field of queen transportation, focusing on reducing physiological stress, optimizing bioengineering parameters of cages and increasing the level of queen adaptation after delivery. The results of field observations in large industrial apiaries show that the use of polymer ventilation cages with built-in feed compartments allows maintaining a stable microclimate even under variable temperature conditions during delivery, which is especially important during transportation by air or truck during hot periods. The use of microchambers for accompanying bees significantly reduces the risk of mechanical damage to the queen due to reduced direct contact, and also helps to maintain pheromone stability, which is essential for successful acceptance of the queen by a new bee family.

Table 1

Types of cages for transportation of queen bees in the USA: design features and biological compliance

| Cage type | Main technical characteristics | Biological compliance with transportation conditions |
|---|---|---|
| Wooden cage with mesh | Natural wood, ventilation holes on the sides, a hole for a candy dish | Provides ventilation, but not sufficiently heat-resistant at extreme temperatures |
| Polymer ventilation cage | Lightweight plastic, perforation over the entire area, impact resistance | Promotes thermoregulation, minimizes stress and losses during long transportation |
| Cage with feed tank | Built-in tank with candy or honey mass | Allows for continuous feeding of the queen and accompanying bees without external contact |
| Individual cage with a micro camera for tracking | Separate cells for 4-6 companion bees, access to food | Reduces the contact load, contributes to better preservation of the uterus during transportation |
| Combination cage (plastic+ grille) | Combination of rigid frame and transparent ventilation grille | Improves monitoring of the uterus, suitable for intensive quality control |

Source: compiled by the author based on [3; 4; 5; 15].

In addition, combined cage designs (plastic with a ventilation grille) provide the ability to visually monitor the condition of the queen without compromising the tightness of the structure, which makes it possible to detect signs of stress or death in time before the party arrives at the apiary. Such structures are effectively integrated into automated selection and accounting systems used in large beekeeping cooperatives. Taken together, these engineering solutions demonstrate high compliance with the modern requirements of commercial beekeeping, contributing to the formation of full-fledged bee colonies in a short time, increasing the level of genetic control and minimizing losses during apiary expansion or seasonal queen replacement.

In the US commercial beekeeping industry, the efficiency of queen bee transportation is assessed by key indicators such as survival rate, acceptance rate in a new family, and reproductive activity after replanting. The design of the cage has a significant impact on these parameters, as it affects the level of bee stress, access to food, ventilation, and the ability to avoid injury. Innovative models that take into account the biological characteristics of the queen bee show significantly better results compared to traditional options. This is why there is an increased interest in the use of improved cages in large-scale farms (Table 2).

Table 2

Influence of cage types on key indicators of queen bee quality in commercial beekeeping in the USA

| Cage type | Average survival rate (%) | Level of queen bee acceptance (%) | Time until the first eggs are laid (hours) | Reproductive activity in the first 5 days (eggs/day) |
|---|---|---|---|---|
| Wooden ventilation | 87,3 | 71,5 | 58 | 780 |
| Polymeric with ventilation | 94,1 | 85,6 | 39 | 1020 |
| With feed tank | 96,5 | 89,3 | 32 | 1085 |
| Isolated with micro-cameras for monitoring | 97,2 | 91,8 | 29 | 1110 |
| Combined (control transparent) | 95,6 | 87,4 | 35 | 1050 |

Source: compiled by the author based on [1; 2; 4; 7; 8].


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The analysis of the above data demonstrates a significant advantage of innovative cage designs over traditional wooden ones. In particular, cages with microchambers for escort bees not only ensure maximum queen survival (over 97%), but also significantly reduce the time to the start of oviposition after planting [9]. This indicates a reduction in stress levels and the preservation of hormonal balance, which is critical for the rapid recovery of reproductive functions. The feed tanks built into modern polymer cages eliminate the problem of temporary starvation during transportation, which was traditionally observed during long deliveries and delayed the recovery of ovogenesis. The level of acceptance of new queens, which in some cases is crucial for the economic success of a beekeeping enterprise, increases by 15-20% when using optimized cages that provide an integrated approach to preserving the biological potential of the queen [11]. The practical implementation of these innovations in leading apiaries not only helps to stabilize bee colonies, but also accelerates the return on investment in the production cycle by reducing losses, increasing the strength of families and improving the genetic renewal of the apiary.

In the U.S. industrial beekeeping system, the speed of formation of a full-fledged bee colony and its level of strength at the beginning of the productive period are the main indicators for assessing the effectiveness of both the breeding program and logistics solutions, in particular the type of queen transportation cages. The bioengineered parameters of the cage directly affect the physiological state of the queen, the time of her acclimatization in the hive, and the quality of eggs laid in the first days. Accordingly, the type of cage determines the rate of bee colony growth, the stability of the behavior of the accompanying bees, the amount of open brood and the readiness of the family for honey collection. Establishing a quantitative relationship between the design of the cage and the indicators of family strength allows optimizing the choice of tools at the breeding stage and increasing the overall profitability of the apiary cycle (Table 3).


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Table 3

Correlation between the type of cage, the rate of development of the bee colony and its strength at the beginning of the productive period

| Cage type | Time to complete acclimatization of the uterus (days) | The number of open broods per Day 10 (cells) | Number of adult bees on day 21 (thousand individuals) | Output of a productive family in 30 days (%) |
|---|---|---|---|---|
| Wooden ventilation | 6,1 | 910 | 12,3 | 71,4 |
| Polymeric with ventilation | 4,3 | 1160 | 15,8 | 83,6 |
| With feed tank | 3,9 | 1250 | 17,2 | 87,9 |
| Isolated with micro-cameras for monitoring | 3,6 | 1320 | 18,5 | 90,1 |
| Combined (control transparent) | 4,1 | 1200 | 16,4 | 85,2 |

Source: compiled by the author based on [4; 6; 7; 11; 12; 16; 17].

Field data show a strong correlation between the type of cage and the dynamics of forming a complete bee colony. Innovative cages that provide adequate ventilation, isolation of companion bees, and access to food help reduce the queen's acclimatization period from more than six to three to four days [5]. This, in turn, accelerates the start of oviposition, increases the area of open brood on the tenth day and stimulates active growth of the population of adult bees by the third week. As a result, the proportion of families that reach a productive level of development in 30 days increases by almost 20% when using modern cages [4]. In commercial terms, this means an increase in the total number of strong families ready for honey harvesting or use in pollination services, which allows US beekeeping farms to improve their economic performance and manage production cycles more efficiently.

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Despite the availability of modern technological solutions in the field of queen bee transportation, a significant number of US apiaries, especially medium-sized ones, continue to use outdated or structurally inadequate cage types, which negatively affects the efficiency of queen bee integration into a new bee colony. The main problem is non-compliance with basic bioengineering requirements, including insufficient ventilation, lack of an autonomous food source, excessive contact between the queen and accompanying bees, or complete isolation without accompaniment, which increases the risk of stress, overheating, and reduced pheromone activity. In such conditions, the queen loses the ability to quickly engage in the oviposition cycle, which delays brood development and reduces the overall strength of the family in the critical period - the first three weeks after replanting [11].

A separate problem is the growing proportion of dead or damaged queens during transportation in cages made of materials that do not absorb shock well or are heat-sensitive, in particular during air transportation or in the heat [6]. In this case, apiaries are forced to re-plant or completely lose potential families, which directly affects production stability and the economic feasibility of costs during the season. In addition, outdated cages often do not allow for quick inspection of the queen without removing her, which makes it impossible to detect death or abnormal conditions in a timely manner while on the road. As a result, there are delays in response, loss of working time and a decrease in the overall acceptance rate of queens in the first cycle of rearing.

Increasing the efficiency of queen bee transportation in profitable US apiaries requires the introduction of cage designs that simultaneously take into account the physiological characteristics of the queen bee, the behavioral dynamics of the companion bees, and the logistical risks of modern forms of delivery. Based on the generalization of open data from field studies and the practice of large farms, it is advisable to recommend the use of cages with autonomous feed tanks that provide

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continuous access to nutrients for 48-72 hours. This option reduces the risk of starvation and loss of uterus during long-distance transportation. Additional efficiency is demonstrated by models with built-in microchambers for accompanying bees, which reduce the risk of contact injury, facilitate queen adaptation and maintain a stable pheromone profile.

From a technological point of view, the structures should be made of a heat-resistant, shock-absorbing polymer that can withstand temperature changes without deformation. It is also necessary to provide perforations throughout the cage body for uniform ventilation, which is critical when packing a large number of queens in commercial batches. It is recommended to use modules with transparent inspection areas that allow for quick monitoring of the uterus without removing it, which reduces stress during transportation. In the future, it is advisable to standardize designs for compatibility with automated inventory, transportation, and replanting systems. All these solutions must meet biosafety requirements, be easily sterilized and reusable. The use of such cages will not only help to preserve the viability of queens, but also increase the overall level of their acceptance and the formation of stronger bee colonies, which is the basis for the sustainable development of highly profitable beekeeping.

**Conclusions and prospects for further research.** It has been established that the type of cage for transportation of queen bees significantly affects the survival rate of queens, the rate of their acceptance and the strength of the formed bee colonies. Innovative designs, in particular with feed tanks and microchambers, provide a stable microclimate, reduce stress and accelerate the recovery of queen reproductive activity, which contributes to the formation of strong productive families and increases the profitability of apiary production.

Among the key problems identified is the use of outdated or non-adapted cages that do not guarantee proper ventilation, protection from overheating and isolation of the accompanying bees. This leads to the loss of queens, delayed

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adaptation, and reduced quality of bee colonies. The lack of standards makes it difficult to automate transportation and quality control.

It is recommended to introduce cages made of heat-resistant materials, with feed compartments, ventilation throughout the body and transparent areas for inspection. Further research should focus on quantitative modeling of the impact of technical parameters on biological outcomes, standardization of designs, and digital integration of data into apiary management systems.

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