

ARCHITECTURE OF DISTRIBUTED DIAGNOSTIC SYSTEM FOR AGRICULTURAL PROCESSING EQUIPMENT: CASE STUDY OF FREEZE-DRYING SYSTEMS

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Abstract. Agricultural processing equipment is increasingly deployed as geographically distributed and digitally interconnected systems, creating new challenges for scalable diagnostics, maintenance, and operational reliability. Freeze-drying equipment represents a particularly demanding application due to the coordinated operation of vacuum, thermal, and control subsystems, while maintaining stable process conditions and product quality under limited service accessibility. This paper presents the architecture of a distributed diagnostic system developed for agricultural processing equipment using freeze-drying systems as a representative case study. Unlike conventional industrial monitoring solutions optimized for stable factory environments, the proposed architecture is designed for geographically dispersed installations operating under heterogeneous hardware configurations and variable communication conditions. The system is based on a modular layered architecture integrating embedded edge nodes, structured telemetry and event logging, secure communication infrastructure, and centralized diagnostic services. The proposed approach enables non-intrusive integration without modification of primary control algorithms and supports scalable deployment across distributed equipment fleets. Architectural applicability was evaluated using a laboratory validation platform consisting of six distributed nodes operating under normal and disturbed communication conditions. Experimental validation confirmed reliable distributed data acquisition, compatibility with heterogeneous embedded platforms, stable synchronization of operational data, and preservation of local functionality during communication interruptions. The results demonstrate that the proposed architecture provides a practical engineering framework for scalable remote diagnostics and distributed condition monitoring in agricultural and food-processing equipment.

Keywords: distributed diagnostics, remote monitoring, freeze-drying, system architecture, IoT.

Introduction

The development of agricultural and food-processing equipment is increasingly influenced by Industry 4.0 concepts, cyber-physical production systems, and Internet of Things (IoT)-enabled infrastructures, enabling closer integration of physical processes with digital monitoring and control environments [1-4]. Freeze-drying equipment represents a demanding example of such systems, as it requires coordinated interaction of vacuum, thermal, and control subsystems to maintain process stability and product quality [5].

At the same time, agricultural processing equipment is often deployed in geographically distributed environments where access to qualified maintenance personnel is limited. Traditional service approaches based on on-site inspection or direct integration with control systems are difficult to scale and may interfere with normal system operation. In addition, small and medium equipment manufacturers typically lack access to comprehensive diagnostic and lifecycle support infrastructures available in large industrial sectors. This creates a gap between increasing system complexity and the level of diagnostic support that can be practically implemented.

Recent advances in Industry 4.0 and IoT technologies have enabled new approaches to distributed monitoring and remote diagnostics based on interconnected devices, structured data exchange, and centralized service functions [1; 2; 4; 6]. These developments support condition-based maintenance strategies aimed at improving system reliability and reducing service costs [7]. However, many existing solutions focus primarily on data collection and data-driven analytics, including machine learning approaches to system health monitoring [8; 9], while providing limited guidance on system-level architectural design, particularly for small and medium-scale industrial applications.

In this context, the design of a distributed diagnostic system requires careful consideration of architectural principles such as modularity, non-intrusive integration, communication robustness, scalability, and support for engineering analysis. These requirements are especially important in systems where modification of control algorithms is undesirable and where deployment conditions include heterogeneous hardware platforms and variable network quality. In addition, the integration of

diagnostic functionality can benefit from structured fault detection and isolation approaches, such as FDIR methodologies, widely used in high-reliability domains [10; 11].

This paper presents the architecture of a distributed diagnostic system designed for agricultural processing equipment, with freeze-drying systems used as a representative case study. The proposed architecture is based on a modular and layered concept that combines embedded control nodes, edge-level data acquisition, secure communication infrastructure, and centralized diagnostic services. The design is derived from practical engineering constraints and enables scalable deployment without interfering with primary control functions. The overall system architecture, showing equipment-level data acquisition, centralized diagnostic services, and remote user interaction is illustrated in Fig. 1.

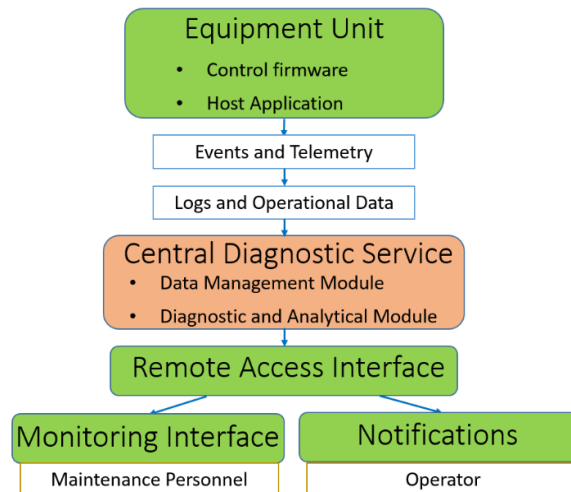


Fig. 1. **Architecture of the distributed diagnostic system**

The main contributions of this paper are: definition of system-level requirements for distributed diagnostic architectures in agricultural processing equipment, development of a modular and layered system architecture supporting non-intrusive integration, demonstration of applicability using freeze-drying equipment as a case study, evaluation of architectural feasibility in a distributed validation environment.

Architectural novelty and domain-specific constraints. Unlike conventional industrial monitoring systems primarily optimized for stable factory infrastructures and homogeneous automation platforms, agricultural and food-processing equipment often operates under significantly different practical constraints. These include geographically dispersed installations, limited access to qualified maintenance personnel, heterogeneous hardware configurations, variable communication quality, and the need to preserve validated control algorithms without intrusive modifications.

Freeze-drying equipment represents a particularly demanding application within this context because process stability depends on coordinated interaction between vacuum, thermal, and supervisory subsystems. In addition, process deviations may directly affect product quality and process efficiency. Existing industrial IoT approaches frequently focus on centralized data acquisition or cloud-level analytics, while providing limited consideration of architecture-level robustness, distributed deployment constraints, and non-intrusive integration requirements relevant for small and medium-scale equipment manufacturers.

The novelty of the proposed work consists in the development of a distributed diagnostic architecture specifically adapted for agricultural processing equipment operating under constrained and heterogeneous deployment conditions. The architecture combines modular layered organization, edge-level buffering and preprocessing, structured event-telemetry acquisition, and centralized diagnostic services while preserving independence of local control systems.

In contrast to conventional monitoring approaches, the proposed architecture is designed to maintain operational functionality during communication disturbances and partial network availability. The system also supports interoperability between heterogeneous embedded platforms and scalable deployment across distributed equipment fleets without structural redesign.

These characteristics distinguish the proposed architecture from generic industrial monitoring systems and establish a practical engineering framework for distributed diagnostics in agricultural and food-processing applications.

System requirements

The architecture of a distributed diagnostic system for agricultural processing equipment must be derived from practical constraints associated with real industrial operation. In contrast to generic IoT monitoring applications, such systems must support continuous equipment supervision without compromising process stability, while remaining scalable and maintainable across distributed installations. For freeze-drying equipment, these requirements are particularly important because process performance depends on coordinated operation of multiple subsystems and because deviations may directly affect product quality [5].

The following main system requirements were identified:

Non-intrusive integration. A primary requirement is the ability to integrate diagnostic functionality without modifying the core control algorithms of the equipment. In many industrial systems, the control layer is closely linked to process safety and validated operating regimes. Diagnostic functions should therefore rely on telemetry, event logs, and external data acquisition rather than intrusive changes to the control firmware. This requirement is also consistent with established principles of fault diagnosis and condition monitoring, where separation between process control and diagnostic interpretation improves robustness and traceability [7; 10].

Data integrity and synchronization. Distributed diagnostics depend on reliable and time-consistent operational data. The architecture must ensure structured acquisition of machine logs, sensor measurements, and control events, together with sufficient synchronization between distributed nodes. Inaccurate timestamps, incomplete records, or inconsistent data streams may compromise fault interpretation and system-level analysis. This requirement is especially relevant for condition-based maintenance strategies and data-driven monitoring environments [7; 12].

Scalability across distributed installations. The system must support operation across multiple equipment units deployed in different locations. This includes the ability to add nodes without substantial redesign of the architecture, while preserving consistent data handling and centralized visibility. Scalability is a key requirement in Industry 4.0 and cyber-physical production environments, where distributed assets are integrated into broader digital service infrastructures [1-4].

Communication robustness. Because equipment may operate in environments with variable network quality, the architecture must tolerate communication delays, temporary disconnections, and partial data availability. Diagnostic support should not depend on uninterrupted connectivity. Local data collection and buffering must remain functional even if centralized services are temporarily unavailable. This is essential for practical deployment in geographically distributed agricultural and industrial systems.

Security and controlled access. Remote monitoring and diagnostic support require secure communication, authentication, and controlled access to equipment data. The architecture must protect both operational data and service functions against unauthorized access. This requirement is especially important in interconnected industrial systems where multiple users, roles, and service layers interact through common digital infrastructure [2; 4; 6].

Support for engineering analysis. The system should not only provide real-time status visibility, but also support engineering analysis of historical behaviour. This includes retention of structured operational logs, traceable event histories, and sufficient diagnostic context for maintenance investigation. Such functionality supports fault isolation, validation of service actions, and gradual refinement of diagnostic logic, including FDIR-oriented reasoning in complex systems [10; 11].

Compatibility with heterogeneous hardware. In practical deployments, distributed systems often include heterogeneous embedded platforms, host systems, and communication interfaces. The architecture must therefore remain independent of any single hardware configuration and allow integration of different controller and host combinations. This requirement is important for long-term maintainability and gradual scaling of the system.

Extensibility. The architecture should allow future integration of additional sensors, analytical tools, and more advanced diagnostic methods, including data-driven approaches. While the present work is architecture-focused, extensibility is necessary to support future evolution toward hybrid monitoring frameworks that may incorporate machine learning, prognostics, and advanced health-management tools [8; 9].

System architecture

The proposed system architecture is designed to enable distributed diagnostic functionality for agricultural processing equipment while ensuring non-intrusive integration with existing control systems. The architecture follows a modular and layered approach, allowing separation of data acquisition, communication, and diagnostic services, and supporting scalable deployment across multiple equipment units. The principles of the architecture are presented in Fig. 1.

Architectural concept. The system is based on a distributed network of equipment nodes connected to centralized diagnostic services. Each equipment unit operates as an independent node capable of generating and locally processing operational data, while higher-level diagnostic and service functions are implemented at the central level.

This approach is consistent with the principles of cyber-physical production systems and distributed industrial infrastructures, where physical processes are integrated with digital monitoring and service layers [1-3]. It enables continuous observation of system behaviour without interfering with primary control functions.

The architecture is designed to support:

- independent operation of equipment units;
- centralized monitoring and coordination;
- integration of heterogeneous hardware platforms;
- gradual system expansion without structural redesign.

Layered architecture. To ensure clarity and scalability, the system is organized into four logical layers (Fig. 2).

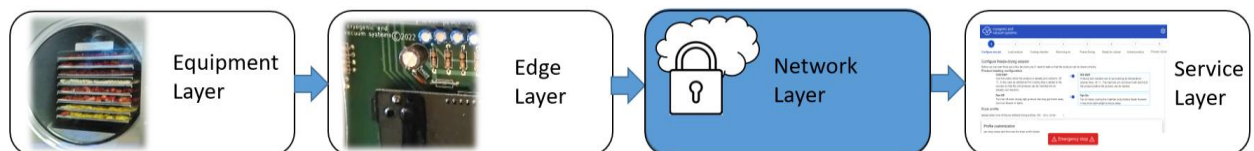


Fig. 2. Layered architecture

Equipment layer. The equipment layer includes physical components such as sensors, actuators, and embedded controllers responsible for process execution. In freeze-drying systems, this layer encompasses subsystems for vacuum generation, thermal control, and process monitoring, which must operate in a coordinated manner to ensure process stability and product quality [5].

This layer generates primary data in the form of sensor measurements and control events.

Edge layer. The edge layer is responsible for local data acquisition, preprocessing, and logging. It operates independently of the control system and collects structured operational data without modifying control algorithms.

Key functions of the edge layer include: acquisition of time-stamped telemetry and event data, local buffering and storage of logs, preliminary data validation and filtering, maintenance of data availability during communication interruptions.

This layer ensures that diagnostic functionality remains non-intrusive and robust under varying operating conditions.

Network layer. The network layer provides communication between distributed equipment nodes and centralized services. It supports data transmission over local and wide-area networks using standard communication protocols.

Given the variability of connectivity in industrial and agricultural environments, the architecture is designed to tolerate: communication delays, temporary loss of connectivity, incomplete or asynchronous data transmission.

These capabilities ensure continuity of system operation and data integrity in distributed deployments.

Service layer. The service layer implements centralized diagnostic and data management functions. It aggregates data from multiple equipment nodes and enables system-level monitoring and analysis.

The main functions of this layer include: storage and management of historical operational data, execution of diagnostic and analytical functions, generation of alerts and system status information, provision of user interfaces for monitoring and maintenance.

This layer enables centralized visibility of distributed systems and supports decision-making processes for maintenance and operation.

Data flow and system interaction. The architecture is based on continuous acquisition and transmission of structured operational data from distributed nodes. Each equipment unit generates time-stamped logs containing sensor measurements, control actions, and system events.

Data flow follows a hierarchical structure:

- data acquisition at the equipment and edge layers;
- local preprocessing and buffering at the edge layer;
- transmission through the network layer;
- aggregation and analysis at the service layer.

Such data-flow organization ensures consistency, traceability, and availability of data across the distributed system. In addition, the architecture supports bidirectional interaction, where centralized services can provide system status information, alerts, and diagnostic feedback to users through remote interfaces.

Design principles and architectural compliance. The proposed architecture is derived from the requirements defined in Section 2 and reflects key system engineering principles.

- Non-intrusiveness: diagnostic functionality is implemented without modification of primary control systems, ensuring process safety and stability.
- Modularity: system components are organized into independent functional units, enabling flexible configuration and future extensions.
- Scalability: the architecture supports expansion from individual equipment units to distributed fleets.
- Robustness: the system maintains functionality under communication disturbances and partial data availability.
- Interoperability: compatibility with heterogeneous hardware and communication environments is ensured.

These principles align with established approaches in distributed monitoring systems and industrial IoT architectures [1; 2; 6].

Case study: freeze-drying equipment

Freeze-drying equipment is selected as a representative application for evaluating the proposed distributed diagnostic system architecture. This type of equipment is widely used in the processing of high-value agricultural and food products, where preservation of structure, nutritional properties, and product quality is essential [5]. The process involves removal of moisture through sublimation under reduced pressure, requiring coordinated operation of multiple subsystems.

A typical freeze-drying process consists of several sequential stages, including freezing, primary drying, and secondary drying. Each stage requires precise control of temperature, pressure, and process duration. Deviations in these parameters may result in incomplete drying, structural degradation of the product, or reduced process efficiency. Consequently, stable operation depends on continuous monitoring of process variables and reliable coordination of system components.

From a system architecture perspective, freeze-drying equipment represents a complex integration of physical processes, embedded control systems, and supervisory software. The equipment includes multiple sensors and actuators, as well as control modules responsible for maintaining process conditions. In addition, host-level software systems are typically used for data acquisition, visualization, and process supervision. This structure makes freeze-drying equipment well suited for integration into distributed diagnostic architectures based on non-intrusive data collection.

Within the proposed architecture, each freeze-drying unit is treated as an independent node in a distributed system (Fig. 3). Operational data are generated in the form of time-stamped logs containing sensor measurements, control actions, and system events. These data are collected at the edge level and transmitted to centralized diagnostic services via the communication layer, as described in the “System architecture” section. This approach enables consistent monitoring of multiple units while preserving independence of local control systems.

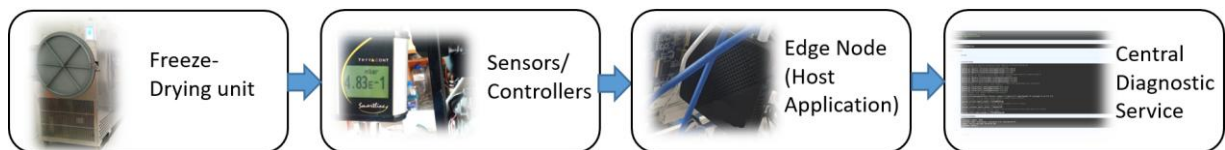


Fig. 3. Integration of freeze-drying equipment into architecture

To evaluate the applicability of the architecture, a laboratory-based validation platform was developed to emulate the operation of multiple freeze-drying units (Fig. 4). The platform reproduces typical process behaviour under both normal and fault conditions and generates structured operational data consistent with real equipment. This allows assessment of system-level characteristics such as data acquisition reliability, communication robustness, and scalability of the distributed architecture.



Fig. 4. Laboratory validation platform

The distributed nature of the system enables simultaneous monitoring of multiple equipment units and supports centralized data aggregation and analysis. This is particularly relevant for installations where several units operate in parallel or are deployed across different locations. The use of structured logs and standardized data exchange facilitates integration with higher-level monitoring and service systems, consistent with the principles of cyber-physical production environments and industrial IoT infrastructures [1-3].

Although the case study focuses on freeze-drying equipment, the proposed architecture is not limited to this application. Similar requirements for non-intrusive diagnostics, distributed monitoring, and scalable service support are present in many agricultural and industrial processing systems. Therefore, the presented approach can be considered a generalizable solution for distributed diagnostic architectures in resource-constrained and geographically dispersed environments.

Architectural validation results. To evaluate the practical applicability of the proposed architecture, a distributed laboratory validation platform was implemented using six interconnected simulator nodes representing independent freeze-drying equipment units. The platform included heterogeneous embedded hardware configurations based on AVR-, ARM-, and x86-compatible systems interconnected through a TCP/IP communication network.

The validation environment was designed to reproduce typical operational conditions relevant to distributed agricultural processing equipment, including normal operation, communication disturbances, temporary disconnections, and asynchronous data transmission. The objective of the validation was not to evaluate specific diagnostic algorithms, but to assess architectural functionality, robustness, scalability, and interoperability under distributed operating conditions.

The experimental platform enabled evaluation of the following architectural characteristics:

- distributed acquisition of telemetry and event data;
- synchronization of operational logs between nodes;
- preservation of local functionality during communication interruptions;
- centralized aggregation of distributed operational data;
- compatibility between heterogeneous embedded platforms;
- scalability of the layered architecture under multi-node operation.

The main validation results are summarized in Table 1.

Table 1

Architectural validation results of the distributed diagnostic system

Parameter	Validation result	Observation
Number of distributed nodes	6	Simultaneous operation confirmed
Embedded platform compatibility	Confirmed	AVR, ARM and x86 architectures
Communication topology	TCP/IP distributed network	Stable operation achieved
Sampling configurations	0.1 s and 1 s	Multi-rate acquisition supported
Log synchronization	Successful	Consistent event correlation observed
Communication disturbance tolerance	Confirmed	Local functionality preserved
Temporary disconnection handling	Successful	Buffered data recovered after reconnection
Centralized data aggregation	Successful	Multi-node visibility achieved
Non-intrusive integration	Confirmed	No modification of control algorithms
Scalability limitations	Not observed in laboratory validation	Stable multi-node operation

The validation results demonstrate that the proposed architecture satisfies the primary system-level requirements defined for distributed agricultural processing equipment. In particular, the system maintained operational continuity under communication disturbances while preserving synchronization and structured acquisition of operational data across heterogeneous embedded platforms.

The experiments also confirmed that the layered architecture supports scalable distributed deployment without requiring modification of primary equipment control systems. This characteristic is especially important for practical implementation in small and medium-scale industrial environments where validated control logic must remain isolated from diagnostic functions.

The obtained results indicate that the proposed architecture provides a stable engineering foundation for implementation of advanced distributed monitoring and diagnostic services in agricultural and food-processing equipment.

Discussion

The presented results demonstrate that the proposed distributed diagnostic system architecture provides a practical and scalable solution for monitoring agricultural processing equipment under real-world constraints. Unlike conventional approaches that rely on direct integration with control systems or localized inspection, the proposed architecture enables system-level visibility through structured data acquisition and distributed communication, without interfering with primary process control.

A key advantage of the proposed architecture is its **non-intrusive design**. By relying on machine logs and sensor data collected at the edge level, the system avoids modification of control algorithms,

which are often tightly coupled to process stability and safety. This is particularly important in industrial environments where validated control logic must remain unchanged. The separation between control and diagnostic layers also improves robustness and traceability, which are essential for engineering analysis and maintenance planning [7; 10].

The architecture is also characterized by a high degree of **scalability and modularity**. Each equipment unit operates as an independent node, allowing incremental expansion of the system without significant redesign. This property is aligned with the principles of cyber-physical production systems and distributed industrial infrastructures, where physical assets are integrated into networked monitoring and service environments [1-3]. In contrast to monolithic monitoring solutions, the proposed approach supports gradual deployment and adaptation to different equipment configurations.

Another important aspect is the system's **ability to operate under imperfect communication conditions**. In many agricultural and industrial contexts, network connectivity is not guaranteed. The use of edge-level data acquisition and buffering ensures that local functionality is preserved even during communication interruptions, while synchronization mechanisms maintain consistency of data once connectivity is restored. This feature is critical for practical deployment in geographically distributed installations.

From a methodological perspective, the architecture provides a structured foundation for integrating different types of diagnostic approaches. While the present work focuses on architectural design rather than specific diagnostic algorithms, the use of structured logs and centralized data aggregation enables implementation of both rule-based and data-driven methods. In particular, the architecture supports future integration of advanced techniques, including machine learning and prognostics, which have been widely investigated for system health monitoring [8; 9]. At the same time, the current design maintains transparency and interpretability, which are often limited in purely data-driven approaches.

The relevance of the proposed architecture is especially pronounced for small and medium equipment manufacturers, who often lack access to comprehensive diagnostic infrastructures. By providing a modular and scalable framework for distributed monitoring, the architecture reduces the barrier to implementing advanced service functions such as remote diagnostics, condition-based maintenance, and centralized system supervision. This contributes to improved operational reliability and more efficient use of maintenance resources.

The architecture can be interpreted as a system-level framework for implementing distributed condition monitoring in resource-constrained industrial environments.

Despite these advantages, several limitations should be noted. First, the effectiveness of the system depends on the quality and completeness of the collected data. Inadequate sensor coverage or insufficient logging may reduce diagnostic capabilities. Second, while the laboratory validation platform enables controlled evaluation of system behaviour, it cannot fully reproduce the variability and complexity of real industrial environments. Finally, the architecture itself does not define specific diagnostic logic, and its performance in practice will depend on the implementation of appropriate analysis methods.

Compared with conventional centralized monitoring architectures commonly used in industrial automation, the proposed system emphasizes non-intrusive integration, distributed resilience, and compatibility with heterogeneous embedded environments characteristic of agricultural processing installations.

Future work should focus on extending the architecture with hybrid diagnostic frameworks that combine rule-based and data-driven approaches, as well as on long-term validation in industrial deployments. In addition, further research is required to optimize data management strategies, improve communication efficiency, and integrate the system with broader digital service platforms.

Conclusions

1. A modular layered architecture for distributed diagnostics of agricultural processing equipment was developed using freeze-drying systems as a representative case study.
2. The proposed architecture enables non-intrusive integration of diagnostic functionality without modification of primary control algorithms, preserving process stability and operational safety.

3. Experimental validation using a six-node distributed laboratory platform confirmed compatibility with heterogeneous embedded hardware platforms, including AVR-, ARM-, and x86-based systems.
4. The architecture demonstrated stable operation under communication disturbances, including temporary disconnections and asynchronous data transmission, while preserving local functionality and data consistency.
5. The layered system organization supports scalable deployment, centralized aggregation of operational data, and integration of distributed monitoring services across multiple equipment units.
6. The proposed approach provides a practical engineering framework for implementing remote diagnostics and distributed condition monitoring in agricultural and food-processing equipment, particularly for small and medium-scale industrial environments.
7. The developed architecture establishes a foundation for future integration of advanced diagnostic and prognostic methods, including hybrid rule-based and data-driven approaches.

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Author contributions

Conceptualization, S. Kravčenko, V. Kravchenko, N. Kuļešovs, K. Carjova and N. Kravčenko; methodology, S. Kravčenko, V. Kravchenko, N. Kuļešovs, N. Kravčenko and K. Carjova; software, validation, V. Kravchenko, S. Kravčenko and N. Kuļešovs; formal analysis, V. Kravchenko, N. Kravčenko, K. Carjova, D. Panova, N. Kuļešovs and S. Kravčenko; investigation, S. Kravčenko, V. Kravchenko, N. Kuļešovs, N. Kravčenko, K. Carjova and D. Panova; data curation, V. Kravchenko, N. Kuļešovs, N. Kravčenko and D. Panova; writing - original draft preparation, S. Kravčenko; writing - review and editing, S. Kravčenko, N. Kravčenko, N. Kuļešovs and K. Carjova; visualization, N. Kravčenko, K. Carjova and D. Panova.; project administration, N. Kravčenko.; funding acquisition, N. Kravčenko. All authors have read and agreed to the published version of the manuscript.

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