

[https://doi.org/10.52326/jes.utm.2026.33\(1\).07](https://doi.org/10.52326/jes.utm.2026.33(1).07)

UDC 662.63:658.58



AVAILABILITY AND MAINTAINABILITY OF EQUIPMENT IN INTEGRATED TECHNOLOGICAL FLOWS FOR SOLID BIOFUEL PRODUCTION: A REVIEW

Teodor Marian^{1,2}, ORCID: 0009-0004-0582-0750

¹CC "AGRI-SOLUTIONS" LLC, 9 Pavel Boțu Str., 2009 Chisinau, Moldova

²PhD student, Technical University of Moldova, 168 Stefan cel Mare Blvd., Chisinau, Republic of Moldova

* Corresponding author: Marian Teodor, marian.t@agrisolutions.md

Received: 02. 20. 2026

Accepted: 03. 18. 2026

Abstract. The transition toward renewable energy sources and the efficient valorization of agricultural residual biomass necessitate increased reliability and efficiency of integrated technological flows for solid biofuel production. The study is based on the hypothesis that the overall performance of the integrated technological flow is primarily determined by equipment located on the critical path and by the operational behavior of working components. The research aims to evaluate equipment availability and maintainability at system level and to identify the limiting links affecting process continuity. The methodology includes the analysis of reliability and maintenance indicators, correlation of availability with functional criticality, and the development of a synthetic technological vulnerability indicator to assess the global risk of unavailability. The results highlight the decisive influence of biomass properties and working component behavior on MTBF, MTTR, and overall availability, emphasizing the need for a systemic and differentiated maintenance approach to enhance system resilience. Furthermore, the findings indicate an uneven distribution of performance within the technological flow and identify densification stages as critical limiting links, followed by mechanical preparation and biomass generation and collection stages. The proposed integrative approach provides an innovative methodological framework for performance evaluation and maintenance prioritization, contributing to reduced unplanned downtime, optimized resource utilization, and improved resilience of solid biofuel production systems.

Keywords: *biomass processing systems, maintenance prioritization, operational availability, pelletizing process, reliability modeling, technological vulnerability indicator, machine working components.*

Rezumat. Tranziția către surse regenerabile de energie și valorificarea eficientă a biomasei agricole reziduale determină necesitatea creșterii fiabilității și eficienței fluxurilor tehnologice integrate de producere a biocombustibililor solizi. Studiul pornește de la ipoteza că performanța globală a fluxului tehnologic integrat este determinată în principal de echipamentele situate pe traseul critic și de comportamentul operațional al organelor de lucru. Scopul cercetării constă în evaluarea disponibilității și mentenabilității echipamentelor la nivel de sistem și în identificarea verigilor limitative care afectează continuitatea

procesului. Metodologia include analiza indicatorilor de fiabilitate și mentenanță, corelarea disponibilității cu criticitatea funcțională și dezvoltarea unui indicator sintetic de vulnerabilitate tehnologică pentru evaluarea riscului global de indisponibilitate. Rezultatele evidențiază rolul determinant al proprietăților biomasei și al comportamentului organelor de lucru asupra MTBF, MTTR și disponibilității globale, evidențiind necesitatea unei abordări sistemice și diferențiate a mentenanței pentru creșterea rezilienței sistemului. De asemenea, rezultatele indică distribuția neuniformă a performanței în cadrul fluxului și identifică etapele de densificare ca verigi limitative critice, urmate de pregătirea mecanică și etapele de generare și colectare a biomasei. Abordarea integrativă propusă oferă un cadru metodologic inovator pentru evaluarea performanței și prioritizarea mentenanței, contribuind la reducerea opririlor neplanificate, optimizarea utilizării resurselor și creșterea rezilienței sistemelor de producere a biocombustibililor solizi.

Cuvinte-cheie: *sisteme de procesare a biomasei, prioritizarea mentenanței, disponibilitate operațională, proces de peletizare, modelarea fiabilității, indicator al vulnerabilității tehnologice, organe de lucru ale utilajelor.*

Abbreviations

ITFSBFP – Integrated technological flow for solid biofuel production from agricultural biomass

RAM – Reliability, Availability and Maintainability

MTBF – Mean Time Between Failures

MTTR – Mean Time To Repair

A – Technical availability

U – Technical unavailability

C – Functional criticality coefficient

K – System interdependence coefficient

IVT – Technologic(al) Vulnerability Indicator

SVB – Solid densified biofuels

1. Introduction

The transition toward renewable energy sources and the efficient utilization of residual agricultural biomass represent essential strategic directions in the context of sustainable development and the reduction of dependence on fossil fuels [1–3]. In this framework, solid biofuels obtained from plant biomass available in the Republic of Moldova constitute a viable energy alternative for strengthening national energy security [4, 5], reducing fossil fuel imports, and promoting circular economy principles in the agricultural sector [6].

The main sources of plant biomass for the production of densified solid biofuels (DSB) available in the Republic of Moldova originate from the agricultural sector, including residues from cereal crops, maize, and sunflower [7], the viticulture sector [8], fruit tree pruning [9], nut tree cultivation [10] and berry shrubs [11]. The structural diversity and physico-mechanical properties of these resources determine specific technological requirements for conditioning and densification processes.

The techno-economic efficiency of solid biofuel production is determined not only by raw material quality or the parameters of grinding, drying, and pressing operations, but also, to a significant extent, by the functional performance of the equipment composing the integrated technological flows for solid biofuel production (ITFSBFP). From a systemic

perspective, ITFSBFP represents the set of interdependent stages of biomass collection, preparation, processing, control, and handling, encompassing both upstream agricultural machinery and downstream conditioning and densification equipment.

During operation, equipment within ITFSBFP is subjected to intense mechanical loads, abrasive wear, variations in biomass moisture and composition, and discontinuous operating regimes. These factors increase failure frequency, lead to unplanned downtime, and reduce overall system productivity [12, 13]. Consequently, equipment availability and maintainability become essential indicators of the operational performance of the technological flow [14, 15].

A review of the scientific literature [16–20], corroborated with the practical experience of agricultural machinery service enterprises [21–23] highlights the direct correlation between the level of technical availability and the quality of maintenance management. Nevertheless, the implementation of modern reliability analysis methods and preventive and predictive maintenance strategies remains limited, particularly in enterprises with restricted technical and financial resources.

Although the literature contains numerous studies focused on optimizing briquetting and pelletizing processes [24–27] research addressing the systemic evaluation of equipment availability and maintainability at the level of the integrated technological flow remains relatively scarce. There is insufficient integration of RAM (Reliability–Availability–Maintainability) concepts, MTBF and MTTR indicators, and modern maintenance management models adapted to the specific characteristics of agricultural biomass.

In enterprises operating integrated flows for the valorization of plant residues, complexity is further increased by resource seasonality, variations in storage conditions, and the technical skill level of personnel, factors that significantly influence equipment operational behavior [28, 29]. Therefore, the analysis of availability and maintainability should be conducted at the level of the integrated technological system rather than at the level of individual equipment.

In this context, the present review article aims to synthesize and critically analyze theoretical and applied contributions concerning the evaluation and improvement of availability and maintainability of equipment used within ITFSBFP, highlighting current trends, existing gaps, and optimization directions adapted to the specific characteristics of the agro-energy sector.

2. Methodology

This study was conducted as a systematic literature review in accordance with the PRISMA 2020 guidelines [30], ensuring transparency, reproducibility, and structured identification of research gaps regarding the availability and maintainability of equipment in ITFSBFP.

The overall review process is summarized in Table 1, which outlines the main methodological stages, corresponding activities, and key data extracted during the analysis.

The review was guided by the following research questions:

1. RQ1: What approaches are used to evaluate the availability and maintainability of biomass processing equipment?
2. RQ2: To what extent are RAM (Reliability–Availability–Maintainability) models applied in integrated solid biofuel production flows?
3. RQ3: Which maintenance strategies (corrective, preventive, predictive) are implemented in biomass densification systems?

Table 1

Systematic literature review process (PRISMA 2020)

Stage	Description	Examples / Data
Protocol	Definition of the review protocol in accordance with PRISMA 2020	Ensures transparency and reproducibility
Research questions	Formulation of key research questions (RQ1–RQ4)	Availability and maintainability assessment, RAM application, maintenance strategies, research gaps
Eligibility criteria	Definition of inclusion and exclusion criteria	Studies published between 2016–2026, English language, RAM indicators, reliability/maintainability focus; exclusions: economic-only studies, lack of explicit methodology, duplicates
Identification	Database search and citation tracking	Scopus, Web of Science, ScienceDirect, MDPI, IEEE Xplore; keywords combining biomass processing and reliability engineering
Screening	Title and abstract evaluation	Records screened: n = 341
Eligibility	Full-text assessment	Full-text articles assessed: n = 134
Inclusion	Selection of studies for final synthesis	Studies included: n = 98
Data extraction	Collection of relevant study variables	RAM indicators (MTBF, MTTR), equipment type, maintenance strategy, analysis level (equipment vs. integrated system)
Quality assessment	Evaluation of methodological rigor and bias risk	Research design clarity, quantitative indicators, RAM model reproducibility
Qualitative synthesis	Grouping and thematic analysis	Equipment reliability; maintenance strategies; RAM model application; system-level approaches
Identification of gaps	Determination of research limitations and missing evidence	Regional underrepresentation, heterogeneous indicators, limited RAM application at system level

4. RQ4: What are the research gaps regarding system-level evaluation at the integrated process flow?

Key aspects of the methodology:

- The literature search covered databases across engineering, energy, and industrial maintenance.
- Studies were limited to those reporting quantitative performance indicators (MTBF, MTTR, failure rates, downtime).
- Screening and full-text assessment were performed systematically according to PRISMA 2020.
- Data extraction included equipment type, system analyzed, maintenance strategies, and level of analysis.

- Due to heterogeneity of methods and indicators, a qualitative synthesis was performed rather than a meta-analysis.
- Research gaps were identified in regional representation, diversity of performance indicators, and the limited application of RAM models at the system level.

This structured approach ensures the review is transparent, reproducible, and directly linked to the research objectives of evaluating equipment performance in ITFSBFP.

3. Results and discussion

3.1. General characteristics of the included studies

Following the application of the PRISMA 2020 methodology, 98 relevant studies were included in the systematic synthesis. Most publications are concentrated in the period 2015–2026, highlighting an intensification of scientific interest in: optimization of biomass densification processes, maintenance digitalization, and the application of RAM models in complex systems.

The geographic distribution of the studies indicates a predominance of research conducted in Europe (Italy, Germany, Poland, Sweden, Romania), as well as in Ukraine, Russia, China, India, and Brazil. However, a limited representation of applied studies in the Republic of Moldova is observed, highlighting a deficit of regionally contextualized research.

The thematic analysis shows that the included studies address the following main directions: qualitative and quantitative characteristics of different types of plant biomass and the finished products obtained from this biomass; solid biofuel supply chains; partial lines for raw material conditioning and processing of plant biomass into pellets and briquettes; reliability of equipment used in crop production and, implicitly, in the production of plant biomass used as feedstock for solid biofuels; technological processes and equipment used for pellet and briquette production; machinery used for biomass size reduction (chippers, hammer mills, sawdust production equipment, and auxiliary machinery).

It is noteworthy that most analyses are conducted at the level of individual equipment rather than at the level of an integrated processing flow.

The synthesis of the 98 studies indicates that most research on reliability, availability, and maintainability (RAM) has been developed at the level of individual equipment or industrial subsystems, without explicitly addressing ITFSBFP. Furthermore, the included studies demonstrate the maturity of RAM concepts in established industries; however, their application to ITFSBFP remains insufficiently substantiated. The specific nature of ITFSBFP – characterized by high functional interdependence, feedstock variability, and accelerated wear of working components – necessitates the development of a RAM model adapted to the agro-energy sector.

3.2. Agricultural Biomass with Energy Potential

Agricultural biomass with energy potential comprises the totality of plant-based materials resulting from agricultural activities that can be utilized through direct or indirect energy conversion processes, particularly in the form of densified solid biofuels (DSB), such as briquettes and pellets [31].

In the context of the transition toward renewable energy sources and the strengthening of the circular economy, this category of resources is gaining strategic importance both at the European level [32–36], and in the Republic of Moldova, where agriculture plays an essential role in the national economic structure [6, 37, 38].

The scientific literature proposes multiple classification criteria (origin, composition, degree of processing, and energy destination) [39–41]. For the conditions of the Republic of Moldova, classification according to the mode of generation is particularly relevant [40, p.14]:

- primary agricultural biomass;
- secondary agricultural biomass;
- dedicated energy biomass.

Primary biomass includes plant material obtained directly from agricultural crops (cereals, industrial crops, forage crops); however, its use for energy purposes is limited by the need to avoid competition with food and feed uses [7]. By contrast, secondary agricultural biomass—represented by agricultural residues and by-products—constitutes the main resource for the production of densified solid biofuels, integrating efficiently into the circular economy paradigm [1, 24].

This classification is consistent with ISO 17225-1:2021, which groups solid biomass according to origin and source, facilitating the evaluation of fuel quality and compatibility with the technical requirements of densification processes [42]. Aligning conceptual delimitation with international standards is essential in a review-type article, as it enables comparability of results and their integration into recent European research frameworks. Aligning conceptual delimitation with international standards is essential in a review-type article, as it enables comparability of results and their integration into recent European research frameworks [43, 44].

From a conceptual perspective, agricultural biomass differs from forest or industrial biomass through the seasonality of production, the heterogeneity of physico-chemical properties, and dependence on agrotechnical practices [41]. These characteristics directly influence harvesting, mechanical preparation, and densification processes, as well as the technical performance of equipment involved in the integrated technological flow for the production of densified solid biofuels (ITF-DSBFP) [31, 39].

Under the conditions of the Republic of Moldova, plant biomass accessible for the production of densified solid biofuels includes three main categories.

Biomass derived from annual crops – wheat and barley straw, corn residues, sunflower residues, and rapeseed residues. Cereal straw exhibits net calorific values ranging between 12 and 15.5 MJ·kg⁻¹ (at 10% moisture) [7]. Corn residues (stalks, leaves, cobs) can reach 4–6 t·ha⁻¹, with a net calorific value of 14.8–16.3 MJ·kg⁻¹, being favorable for densification due to their lignocellulosic structure [38]. Sunflower husks are distinguished by an energy value of approximately 14–16 MJ·kg⁻¹, but with a higher ash content (3–5%), an aspect relevant for blend formulation and equipment wear [45, 46].

Lignocellulosic biomass derived from fruit trees and berry shrubs is considered one of the most accessible sources for the production of solid densified biofuels (SDB), due to its high energy density and favorable lignin content [47]. Typically, SDB are obtained from residues generated during crown training and maintenance pruning, annual fruiting cuts, removal of dry or diseased branches, clearing of aged specimens, or from waste resulting from nursery plant production [48–50].

Agricultural lignocellulosic biomass exhibits favorable energy characteristics due to its high lignocellulose content and significant calorific value [47, 49], which make it suitable for conversion into SDB such as pellets and briquettes [48], findings also confirmed by our previous research [37].

Biomass resulting from viticultural activities is found in the form of canes and residues generated from the annual pruning of grapevines. Although available in significant quantities, its potential remains largely underutilized [51]. Along with other agricultural residues, it contains lignin, hemicellulose, and cellulose [52, 53], which are essential components for the production of biofuels. International studies [54–58] as well as research conducted in the Republic of Moldova and Romania [8, 47, 59–62] confirm the feasibility of converting these resources into solid biofuels. However, numerous authors have shown that many agricultural residues, when used in their natural form, do not meet ENplus quality requirements [63].

Biomass obtained from dedicated energy crops (short-rotation coppice systems) is derived from non-food agricultural crops cultivated exclusively for the production of energy biomass. Relevant examples include *Miscanthus giganteus* [64], *Salix* spp. [65], poplar (*Populus L.*) [66], and energy sorghum [67]. These crops are characterized by high biomass productivity, a predictable life cycle, and the possibility of standardized mechanized harvesting [68, 69].

Most agricultural biomass used for energy purposes consists of residues and by-products, which gives it a central role within the circular economy and in the sustainable valorization of organic remnants generated during the technological processes of primary agricultural production. In this context, increasing attention is being paid to the implementation of agroecological practices that contribute to reducing the carbon footprint and strengthening a sustainable rural economy [70].

In turn, strengthening a sustainable rural economy requires the recycling and reuse of residues, the reduction of resource waste, and the development of new value chains based on the valorization of agricultural waste and by-products [6, 71]. Within this framework, assessing the quantitative and qualitative potential of agricultural residues becomes an essential element for integrating plant biomass into renewable energy chains through its conversion into densified solid biofuels [72–74].

From this perspective, scientific interest lies not only in determining the physicochemical characteristics of agricultural biomass from the standpoint of final product quality, but also in analyzing their techno-economic implications [1]. In particular, it is necessary to investigate how biomass properties influence equipment wear rates, maintenance intervention frequency, the technical availability of ITFSBFP, the stability of process parameters, and, consequently, the consistency of final product quality [75, 76].

The analysis of the specialized literature on agricultural plant biomass with energy potential highlights that it represents not only an available renewable resource, but also an integrating element of the ITFSBFP, whose efficient valorization depends on the correlation between the physicochemical characteristics of the raw material, the technological infrastructure, and the maintenance strategies applied to the equipment involved in the ITFSBFP.

Consequently, deepening research on this technological link within the ITFSBFP is both timely and justified, and may be oriented in two major directions to improve system availability and maintainability:

1. Correlative evaluation of the quantitative and qualitative potential of agricultural residues according to origin and analysis of their impact on the availability and maintainability of equipment used throughout the ITFSBFP;

2. Optimization of the compatibility between biomass properties and the technological requirements of densification processes in order to reduce equipment wear and stabilize operational performance.

3.2. Particularities of the Integrated Technological Flow for the Production of Solid Biofuels from Agricultural Biomass

The integrated technological flow for producing densified solid biofuels (ITFSBFP) from agricultural biomass represents an integrated technical system composed of a sequence of interdependent processes, beginning with residue generation in the field and ending with delivery of the finished product to the consumer. Unlike conventional industrial lines, the ITFSBFP has an open, seasonal, and variable character, determined by biomass characteristics and agro-climatic conditions.

In the specialized literature, pellet and briquette production is predominantly analyzed at the level of the solid biofuel supply chain [24, 77–80]. However, in the case of agricultural biomass, an integrated flow approach is required, including the following main links: biomass formation and generation through agricultural processes (cultivation, maintenance, harvesting); collection and handling of residues (baling, preliminary chopping, internal transport); transport and storage of raw materials, significantly influenced by moisture content and seasonality; biomass preconditioning (size reduction, drying, impurity separation); densification through briquetting or pelletizing; as well as cooling, packaging, and storage of the finished product.

The integration of these stages into a unified system constitutes what, in this study, is defined as the ITFSBFP. Unlike the narrow technological flow limited to the industrial processing stage, the ITFSBFP includes both the core production operations and the stages of generation, collection, handling, preservation, pretreatment, conditioning, processing, quality control, and management of auxiliary flows. These stages are characterized by a defined sequence, specific technological regimes, and strong functional interdependencies between primary and auxiliary equipment, which confer a high sensitivity of the flow to failures or unplanned stoppages.

The stable and efficient operation of the ITFSBFP is directly conditioned by the level of availability and maintainability of its component equipment [81]. Given the high degree of functional interdependence among technological operations, the unavailability of a critical unit disrupts process continuity and may lead to production flow interruption, with negative effects on productivity, finished product quality, and delivery continuity within the supply chain [27].

Equipment availability reflects the ability of machinery to be operational when required by the technological process and is influenced by failure frequency, downtime duration, and the efficiency of maintenance activities [82, p. 171-175]. In the ITFSBFP, overall system availability is determined by the availability of each component unit, especially those located along the critical path of the flow, such as size-reduction, drying, and pressing equipment. In this context, availability must be analyzed as a property of a complex technical system [83], characterized by a high probability of failure during biomass production, conditioning, and processing stages, increased sensitivity to variations in raw material properties, the need for preventive and predictive maintenance, and the importance of real-time monitoring of technological parameters.

Equipment maintainability expresses the ability of machinery to be serviced and restored to operational condition within a minimal time interval through corrective or preventive interventions performed under given technical and organizational conditions [82, p. 107-112]. Within integrated technological flows, characterized by intense mechanical stresses and variable operating regimes, maintainability is influenced by the equipment's

design solutions, the accessibility of wear-prone components, the degree of spare parts standardization, and the qualification level of maintenance personnel. This situation necessitates decision-making regarding the adaptability and configuration of the equipment group used throughout the ITFSBFP[84].

The interdependence between availability and maintainability is particularly relevant in the ITFSBFP, since low maintainability leads to prolonged downtime and, implicitly, reduced equipment availability. In this context, optimizing maintenance activities contributes not only to increasing the effective operating time of equipment but also to stabilizing the technological process and improving the overall performance of the flow.

Specialized literature confirms the maturity of RAM models in established industries; however, their application in the agro-energy sector remains insufficiently developed. Therefore, the development of a RAM model adapted to the specific characteristics of agricultural biomass and the structure of the integrated technological flow is justified.

In conclusion, the ITFSBFP based on agricultural biomass represents an integrated system characterized by high raw material variability, strong functional interdependence, and severe mechanical stress regimes. These particularities require a systemic approach to availability and maintainability, grounded in correlating biomass properties with the technical performance of the equipment involved in the process.

3.3. Specific Features of the Availability and Maintainability of Equipment in ITFSBFP: Case Study of Working Components

The scientific literature indicates that, within ITFSBFP, the working components of equipment represent the elements most exposed to mechanical, abrasive, and dynamic stresses, constituting the critical link in determining the actual availability of the system [15, 85]. Although RAM analysis is frequently performed at the equipment level, recent studies emphasize that the overall performance of technological flows is predominantly determined by the in-service behavior of active components—knives, hammers, screens, rollers, dies, and screw conveyors, etc.[86].

Research on agricultural biomass processing shows that variability in moisture content, the presence of mineral particles, and dimensional heterogeneity generate severe wear and failure regimes, directly influencing maintenance frequency and downtime duration [87]. In this context, the literature recommends correlating availability analysis with MTBF and MTTR indicators, which reflect the real operational behavior of working components and vary significantly depending on the stage of the technological flow [88].

During the biomass generation and collection stage, studies indicate that the active elements of agricultural machinery – knives, discs, tines, and pickup systems – are subjected to combined shock, abrasion, and mechanical fatigue stresses [13]. The presence of mineral impurities, chemical elements, and hard particles accelerates wear, promotes corrosion processes, and contributes to the formation of microcracks, thereby reducing component service life [89, 90]. The availability of these machines is influenced by the wear level of active components, the frequency of adjustments, and pedoclimatic conditions, while maintainability depends on constructive accessibility and assembly modularity [91]. Operational experience shows that intervention times are often prolonged due to the lack of standardized spare parts and the seasonal nature of operation, which leads to defect accumulation during peak periods [92]. Although failures at this stage have an indirect impact

on the industrial flow, instability in raw material supply may affect the continuity of subsequent stages.

As biomass enters the industrial processing stage, mechanical preparation becomes the first link positioned on the critical path of ITFSBFP. Studies on biomass shredding and grinding show that working components – knives, hammers, counter-knives, screens, and rotor shafts – operate at high rotational speeds and are subjected to intense abrasive wear [93]. The literature identifies the main degradation mechanisms as edge dulling, fatigue cracking, rotor imbalance, and system blockage caused by variations in biomass granulometry or moisture [94, 95]. At this stage, MTBF is relatively low compared to other links, and unplanned stoppages directly affect the entire system. Studies emphasize that maintainability depends on the speed of component replacement, the possibility of dynamic balancing, and the existence of standardized adjustment procedures, which justify the implementation of condition monitoring and predictive maintenance.

The analysis of the technological flow logically leads to the final densification stage, which completes the transformation of biomass into a standardized product in terms of dimensions and energy content. In industrial practice, this stage may be performed either through briquetting or pelletizing, the choice of technology being determined by production specifics, market requirements, available raw materials, and the enterprise's level of automation. Consequently, availability and maintainability assessment must be adapted to the characteristics of the equipment used in the final densification stage.

The literature highlights that, regardless of the adopted technology, the densification stage occupies a critical position within the predominantly series configuration of ITFSBFP, since any functional disturbance is directly transmitted to the entire system. In briquetting presses, screws or pistons and forming dies are subjected to abrasive and plastic wear generated by high pressures and friction temperatures, while availability is strongly influenced by the stability of biomass properties [96]. In pellet presses, press rollers and perforated dies operate under intense mechanical loads and are highly sensitive to variations in raw material granulometry and moisture, highlighting the functional interdependence between mechanical preparation and final densification.

Studies indicate that the main causes of reduced availability in the densification stage include wear of working components, blockage of compression or extrusion channels, process parameter instability, and bearing overload, while MTBF is directly influenced by the quality of prior mechanical preparation. Thus, regardless of the technological solution adopted, the final densification stage represents a critical point in the flow, exerting a major influence on production continuity and the overall performance of ITFSBFP.

Overall, the literature converges on the conclusion that the global availability of ITFSBFP is determined by the functional interdependence of technological links and by the operational behavior of working components, which concentrate the primary degradation mechanisms and generate significant variations in MTBF and MTTR indicators. The analysis of technological stages reveals structural differences in stress levels, failure frequency, intervention complexity, and the impact of stoppages on process continuity.

Under these conditions, in order to comparatively highlight the influence of each equipment group on global availability and to facilitate a systemic interpretation of operational performance, it is necessary to synthesize RAM indicators in a structured form. Such an approach enables the correlation of reliability and maintainability parameters with

functional positioning within the technological flow and provides the basis for identifying critical links.

For this purpose, the following section presents a comparative synthetic scheme of RAM indicators for the four main equipment groups within ITFSBFP, highlighting critical working components, estimated MTBF and MTTR levels, their impact on global availability, and specific maintainability characteristics.

3.4. Comparative synthetic scheme of RAM indicators for the four groups of equipment

The RAM analysis has been applied in various fields to support maintenance decision-making, while the reliability and maintainability of components are used to evaluate the availability of technical systems [93]. In the case of integrated technological flows for the production of solid biofuels from agricultural biomass, comparative quantitative information regarding RAM indicators remains limited, and existing studies predominantly provide analyses at the level of individual equipment or qualitative descriptions of operational behavior. This gap complicates the systemic evaluation of the operational performance of integrated flows.

However, available research highlights significant differences in failure behavior and maintenance requirements between technological stages, emphasizing the influence of mechanical stresses, operating conditions, and the complexity of interventions on system functioning. Complementarily, practical experience accumulated in the operation and maintenance of these flows in enterprises confirms substantial variations in failure frequency and maintenance requirements among technological stages, highlighting the need for a systemic approach to availability.

The differentiated study of the four equipment groups within the ITFSBFP highlights distinct particularities regarding MTBF, MTTR, and their impact on overall availability. To facilitate a systemic and comparative interpretation of these characteristics, it is necessary to synthesize the available information in a structured form that allows the functional and positional differences within the technological flow to be clearly identified [97].

Since the ITFSBFP configuration is predominantly of a series type, the influence of each link on overall performance is not uniform. Therefore, a comparative analysis of RAM indicators must consider not only technical parameters (MTBF and MTTR), but also positioning along the critical path and the maintainability specifics of each equipment category [98]. For this purpose, Table 2 presents a comparative synthetic scheme of the main RAM indicators for the four analyzed equipment groups, highlighting critical working elements, estimated MTBF and MTTR levels, their impact on overall availability, and maintainability particularities, based on trends documented in the scientific literature and practical experience in the operation and maintenance of equipment used in ITFSBFP.

The comparative analysis of the data synthesized in the table highlights significant functional differences among the equipment groups within the ITFSBFP, determined by the level of mechanical stress, their position in the technological flow, and the complexity of maintenance interventions. Equipment used for agricultural operations and biomass handling exhibits a medium MTBF with seasonal variations, while the low–medium MTTR reflects the simplicity of interventions and the accessibility of components. Their impact on overall availability is indirect, since failures affect raw material supply without immediately causing the shutdown of the industrial flow.

Table 2

Comparative synthetic scheme of RAM indicators for the main equipment groups within ITFSBFP

Equipment Group	Critical Working Components	Estimated MTBF	Estimated MTTR	Impact on Overall System Availability	Maintainability Characteristics
Equipment for agricultural operations and biomass handling	knives, discs, tines, pickup mechanisms	medium (seasonally variable)	low–medium	indirect (affects feedstock supply to the process flow)	frequent but relatively simple interventions; strong dependence on pedoclimatic conditions
Mechanical pre-processing equipment (chipping, shredding)	hammers, screens, rotors, shafts	low–medium	medium	major (positioned on the critical process path)	requires precise adjustments, dynamic balancing, and systematic wear monitoring
Briquetting equipment	screw/piston assembly, compression chamber, dies	medium	high	direct impact on production continuity	complex disassembly procedures; intensive wear in the compression zone
Pelletizing equipment	press rollers, perforated dies	medium	high	critical (can completely stop the production flow)	fine adjustments required; high sensitivity to biomass properties; high replacement cost of components

In contrast, mechanical pre-processing equipment operates under intensive loading regimes and is positioned on the critical path, which explains the low–medium MTBF and medium MTTR. Although interventions are not as complex as in the densification stages, the need for precise adjustments, dynamic balancing, and wear monitoring gives this equipment group a major impact on process continuity.

The densification stages introduce more severe operating conditions, characterized by high pressures and intense friction. Briquetting equipment exhibits a medium MTBF but a high MTTR, determined by the complexity of disassembly, pronounced wear of compression elements, and the need for technological adjustments after intervention. Their impact on availability is direct, as equipment stoppage interrupts production.

Pelletizing equipment, although having an MTBF similar to briquetting machines, is distinguished by high sensitivity to variations in biomass properties and strict adjustment requirements, which maintain MTTR at a high level. Due to their final role in the technological flow, their failure can lead to a complete production shutdown, giving them a critical impact on overall availability.

The high mean time to repair (MTTR) for briquetting and pelletizing equipment is determined by their critical role in the technological flow and the complexity of the required

interventions. Failure of these units leads directly to production stoppage, as there are no technological bypass options for the densification stage; therefore, the intervention duration inevitably includes process downtime. Maintenance operations involve complex disassembly of compression elements, replacement of components subjected to intense wear, realignment, and functional adjustments after reassembly. In addition, high mechanical and thermal stresses, intense friction, and variability in biomass properties accelerate component degradation, increasing both the frequency and difficulty of interventions. After completion of the work, restoring stable operating conditions requires adjustment of technological parameters and verification of product quality, which prolongs the total time required to return to normal production capacity. Overall, these factors justify classifying MTTR for briquetting and pelletizing stages as high.

Overall, the comparative analysis reveals a progressive increase in technological criticality from the agricultural stage to the densification stages, accompanied by increasing maintenance complexity and intervention duration. These differences justify a differentiated approach to maintenance strategies and support the need to correlate RAM indicators with functional criticality when evaluating the operational performance of the ITFSBFP.

These differences in MTBF and MTTR levels, as well as the distinct impact of each link on process continuity, highlight that the operational performance of the technological flow is determined by the cumulative availability of its component stages. Since the ITFSBFP operates predominantly in a series configuration, the overall system availability can be expressed by the following relationship:

$$A_{ITFSBFP} = \prod_{i=1}^n A_i \quad (1)$$

where A_i represents the availability of each technological link.

Relation (1) highlights that a reduction in availability at a single stage—typically the pelletizing/briquetting stage—produces a multiplicative decrease in the overall availability. Thus, the results synthesized in Table 2 constitute the foundation for the mathematical modeling of overall performance and for identifying the system's limiting link.

To apply relation (1), it is necessary to determine the individual availability of each equipment group. From the perspective of reliability theory, technical availability depends directly on the mean time between failures (MTBF) and the mean time to repair (MTTR). Therefore, technical availability is determined by the relation:

$$A = \frac{MTBF}{MTBF + MTTR} \quad (2)$$

Relation (2) highlights the mechanism through which variations in MTBF and MTTR influence availability. A decrease in MTBF or an increase in MTTR leads to a reduction in the value of A , and in a series system the effect propagates multiplicatively to the overall availability.

Determining technical availability provides a quantitative assessment of the performance of each technological link; however, the real impact on system operation depends not only on the level of availability but also on the functional importance of the equipment within the technological flow. In systems organized predominantly in a series configuration, the shutdown of certain equipment may have disproportionate effects on process continuity. Therefore, correlating availability with functional criticality enables the identification of links with major impact on operational performance.

For this purpose, the main equipment groups are positioned in a criticality–availability matrix, presented in Table 3, which synthesizes trends highlighted in the specialized literature and practical experience regarding the impact of downtime on process continuity.

The distribution of equipment groups within the criticality–availability matrix highlights clear differences in the operational impact of downtime. Equipment used for agricultural operations and biomass handling falls within the operational control zone, as failures affect the supply of the process flow without causing immediate stoppages. Mechanical preparation equipment is positioned in the technological critical zone, playing a decisive role in process continuity due to its location on the critical path and the intense mechanical stresses involved.

Table 3

Criticality–availability matrix for main equipment groups

Equipment group	Estimated availability	Functional criticality level	Matrix zone	Operational impact	Recommended maintenance priority
Equipment for agricultural operations and biomass handling	medium	medium	operational control zone	influences supply	seasonal preventive maintenance
Equipment for mechanical preparation	medium–low	high	technological critical zone	may interrupt the process flow	predictive monitoring and wear control
Briquetting equipment	medium	critical	strategic critical zone	interrupts production	optimization of interventions and wear-parts management
Pelletizing equipment	medium–low	critical	strategic critical zone	may completely stop the process	advanced predictive maintenance and continuous monitoring

The distribution of equipment groups within the criticality–availability matrix highlights clear differences in the operational impact of downtime. Equipment used for agricultural operations and biomass handling falls within the operational control zone, as failures affect the supply of the process flow without causing immediate stoppages. Mechanical preparation equipment is positioned in the technological critical zone, playing a decisive role in process continuity due to its location on the critical path and the intense mechanical stresses involved.

The densification stages exhibit the highest systemic impact. Both briquetting and pelletizing equipment are classified in the strategic critical zone because they function as final stages of the densification process, and the stoppage of either leads to production interruption. While pelletizing can cause total flow shutdowns due to its high sensitivity to biomass property variations and strict adjustment requirements, briquetting involves complex interventions and long repair times, resulting in an equivalent operational impact.

Overall, the matrix reveals a progressive increase in technological criticality from the agricultural stage to the densification stages, confirming the need to prioritize maintenance strategies according to the systemic impact of each link and highlighting the critical role of the final stages in ensuring the operational continuity of the ITFSBFP

From a mathematical standpoint, the overall availability of the system can be expressed by the generalized relation:

$$A_{global} = \prod_{i=1}^n A_i \quad (3)$$

where A_i represents the availability of each technological link.

Considering that the densification stages fall within the strategic critical zone, and their stoppage leads to production interruption, the evaluation of operational performance cannot be carried out solely based on availability. For this reason, in order to quantify the risk associated with stoppages and to highlight the systemic impact of critical links, availability must be analyzed through its complement, the technical unavailability, defined as:

$$U_i = 1 - A_i \quad (4)$$

where U_i represents the unavailability of the technological link and A_i its availability. This relationship highlights the proportion of time during which the equipment cannot fulfill its operational function and allows the direct evaluation of the risk of process interruption.

However, technical unavailability does not sufficiently reflect the different functional impact of system links on overall performance. To integrate the systemic impact of downtime, the functional criticality coefficient C_i is introduced, which weights unavailability according to the role of each stage, defined by the following relation:

$$C_i \in \{0,25; 0,50; 0,75; 1,0\} \quad (5)$$

where the values correspond to the following criticality levels: low (0.25), medium (0.50), high (0.75), and critical (1.00).

The introduction of coefficient C enables the transition from a strictly technical assessment of unavailability to an integrated techno-functional analysis, laying the groundwork for the formulation of the synthetic technological vulnerability indicator, in which unavailability is weighted according to the systemic importance of each link.

To quantify in a unified manner the contribution of technical unavailability (relation 4) and the functional criticality coefficient (relation 5) to the overall vulnerability of the ITFSBFP, these two components must be integrated into a synthetic indicator.

Furthermore, within a predominantly series flow, the influence of a link on system performance is also determined by its degree of structural interdependence. Links positioned on the critical path, without technological redundancy, exert a stronger impact on overall performance than partially redundant ones. To reflect this structural dimension, the **systemic interdependence coefficient** K is introduced.

By correlating unavailability U_i , functional criticality C_i , and the systemic interdependence coefficient K_i , the technological vulnerability indicator for each link is obtained:

$$IVT_i = U_i \cdot C_i \cdot K_i \quad (6)$$

The aggregation of individual contributions leads to the global vulnerability indicator:

$$IVT_{global} = \sum_{i=1}^n IV T_i \quad (7)$$

A higher IVT level indicates greater exposure to technological risk and the need to prioritize interventions.

To illustrate the methodological applicability of the proposed model, a conceptual application of the technological vulnerability indicator (IVT) is presented for the main equipment groups within the ITFSBFP. Since the present study has a synthesis character, the included values are indicative and aim to highlight the integration of technical unavailability, functional criticality, and systemic interdependence in technological risk assessment. The proposed tabular structure may serve as a standardized framework for presenting and interpreting results obtained in future experimental research.

Table 4 summarizes the estimated values of availability (A), unavailability (U), criticality (C), interdependence coefficient (K), and the resulting indicator IVT_i , facilitating the identification of the link with the dominant impact on overall performance.

Table 4 does not present experimental results; rather, it provides an example of operationalizing the proposed model for assessing technological vulnerability. The structure of the indicator enables the quantification of each subsystem's contribution to the overall risk of unavailability and facilitates the identification of the system's critical links. By integrating RAM parameters with functional criticality and systemic interdependence, the model offers an analytical tool for prioritizing maintenance interventions and optimizing operational performance.

Table 4

Conceptual model for assessing the technological vulnerability of equipment groups within the ITFSBFP

Equipment Group	A	U	C	K	IVT	Contribution to Global Risk
Equipment for agricultural operations and biomass handling	A ₁	U ₁	C ₁	K ₁	IVT ₁	low
Equipment for mechanical preparation	A ₂	U ₂	C ₂	K ₂	IVT ₂	significant
Briquetting equipment	A ₃	U ₃	C ₃	K ₃	IVT ₃	major
Pelletizing equipment	A ₄	U ₄	C ₄	K ₄	IVT ₄	dominant

In future research, completing the table with experimentally determined values will enable the comparative evaluation of technological systems, validation of the proposed model, and support decision-making aimed at increasing availability and reducing technological vulnerability.

4. Conclusions

The review highlights that the operational performance of the ITFSBFP has a pronounced systemic character, being determined by the functional interdependence of technological links, feedstock variability, and the operational behavior of equipment working components.

The valorization of agricultural residual biomass has strategic relevance for energy security and the circular economy, while the performance of technological infrastructure and equipment significantly influences the efficiency of agro-energy chains. In this context, equipment availability and maintainability represent essential indicators of process stability and production continuity.

The application of the PRISMA methodology enabled the identification of relevant studies and revealed important gaps, including the predominance of equipment-level analyses, the heterogeneity of performance indicators, and the limited application of RAM models at the level of integrated technological flows. These findings support the need for a systemic approach adapted to agro-energy systems.

The synthesis of the analyzed studies indicates an increasing scientific interest in densification process optimization and maintenance digitalization, alongside a deficit of regionally contextualized research. The ITFSBFP is characterized by high functional interdependence, biomass variability, and severe wear regimes, which require the development of RAM models adapted to these specific operating conditions.

Agricultural biomass acts as an integrating element of the technological flow, while its physicochemical properties influence equipment wear, maintenance frequency, and process stability. Correlating biomass characteristics with equipment performance is essential for improving availability and reducing degradation of working components.

The ITFSBFP operates as an open, seasonal, and variable technical system whose operational stability depends directly on the availability and maintainability of equipment located along the critical path, particularly within the mechanical preparation and densification stages.

Working components represent the critical elements determining actual system availability, being subjected to severe mechanical, abrasive, and dynamic stresses. Variations in biomass moisture, the presence of mineral impurities, and dimensional heterogeneity accelerate wear and directly influence MTBF and MTTR values.

The comparative RAM analysis of the main equipment groups reveals significant functional differences among technological stages and confirms that global availability is structurally determined by links positioned on the critical path within a predominantly series configuration. The densification stage, particularly pelletizing, exhibits the highest systemic impact due to intervention complexity, sensitivity to biomass properties, and extended repair duration.

The integration of RAM indicators with functional criticality and systemic interdependence led to the development of the IVT, representing the main contribution of this study. By integrating RAM indicators with functional criticality and systemic interdependence, the IVT enables the quantification of the global risk of unavailability and the prioritization of maintenance interventions, while also highlighting the decisive influence of biomass properties and working component behavior on MTBF, MTTR, and overall availability.

From a practical perspective, the proposed methodological framework can support agricultural machinery service enterprises in optimizing maintenance strategies, reducing unplanned downtime, improving spare parts management, and supporting technological modernization decisions. Integration of this framework into predictive maintenance and condition monitoring strategies can enhance operational resilience and competitiveness in agro-energy systems.

Overall, the study provides an integrated conceptual and methodological framework for evaluating and optimizing the performance of solid biofuel production systems and demonstrates the necessity of applying differentiated maintenance strategies based on functional criticality and technological vulnerability.

Looking ahead, future research should focus on the experimental validation of the IVT using operational data from real technological flows and on the development of dynamic RAM models integrated with predictive monitoring and condition-based maintenance. Further investigations are also needed to deepen the understanding of the relationships between biomass properties and wear mechanisms of working components, optimize feedstock–equipment compatibility to stabilize processes and reduce component degradation, and evaluate hybrid technological configurations and functional redundancy solutions to increase system resilience. Expanding research at the regional level will contribute to the development of models adapted to the specific agro-energy conditions of the Republic of Moldova.

Acknowledgments: This research was supported by the program Complex Bilateral Projects with the Republic of Moldova (PCB-RO-MD-202), project no. PN-IV-PCB-RO-MD-2024-0336, within PNCDI IV. Additional support was provided by project no. 20.80009.5107.15, “Development and implementation of best practices for sustainable agriculture and climate resilience (GREEN/020407)”, which ensured technical and logistical assistance for the qualitative and quantitative characterization of agricultural plant biomass.

The author gratefully acknowledges the Research Management Directorate and the Doctoral School of the Technical University of Moldova for logistical support. Special thanks are extended to the Research Center Mechanical Engineering and Materials (TUIASI), SC BASADORO AGROTEH SRL, and Agrisolution SRL for their valuable support in collecting data on the availability and maintainability of equipment used in the integrated solid biofuel production flow.

Conflicts of Interest: The author declares that there are no conflicts of interest regarding the publication of this article. The research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest. All data presented in this study are original and were generated by the author within the reported research. The author confirms that the manuscript has not been previously published and is not under consideration for publication elsewhere.

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Citation: Marian, T. (2026). Availability and maintainability of equipment in integrated technological flows for solid biofuel production: a review. *Journal of Engineering Science*. 2026, 33 (1), pp. 97-119. [https://doi.org/10.52326/jes.utm.2026.33\(1\).07](https://doi.org/10.52326/jes.utm.2026.33(1).07).

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