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A Bibliometric and Literature-Based Overview of Biomass Pre-treatment and Conversion Technologies Modelling with Aspen Software

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Abstract – Biomass is central to carbon-neutral energy systems, yet its heterogeneity and low bulk density hinder efficient conversion. Pre-treatment operations (drying, size reduction, torrefaction, and densification) are essential for stabilizing feedstock properties and enhancing conversion performance. This study examines how these stages are represented in Aspen Plus models and identifies methodological gaps through bibliometric and literature analyses. Performance analysis shows that most Aspen-based studies focus on gasification and pyrolysis, while explicit modelling of pre-treatment remains limited. Examination of thirteen representative papers confirms that biomass is typically assumed to be an already pre-treated input, despite the strong influence of feedstock characteristics on reactor behaviour, energy efficiency, and emissions. Scientific mapping highlights active collaboration among European countries but limited representation from the Baltic region. Three potential improvement scenarios for a Latvian pellet plant demonstrate how Aspen Plus can link feedstock properties with technical and economic performance, supporting the optimization of pelletisation and pre-treatment processes crucial for advancing sustainable bioenergy systems.

***Keywords* – Aspen Plus; Aspen software; biomass utilization; combustion; gasification; overview; pelletisation; pyrolysis; sustainable development goals.**

1. INTRODUCTION

Biomass is foundational to climate-aligned energy systems because it participates in the short-cycle carbon flux that limits net greenhouse impact [1]. Its deployment remains constrained by heterogeneity in origin, physical structure, and biochemical composition, together with low bulk density that increases logistics burden, limits reactor throughput, and complicates process control [2], [3]. Feedstock quality exerts decisive techno-economic influence; e.g., elevated moisture content increases specific energy demand for drying, increasing transportation costs and decreases the effective lower heating value delivered to conversion units [4]. These factors complicate the configuration of thermochemical pathways, affecting reaction kinetics, conversion efficiency, and pollutant formation. As illustrated in Fig. 1, within the overall biomass utilization system boundaries, the production of intermediates for high-value outputs such as hydrogen or liquid biofuels almost always requires a dedicated pre-treatment stage to stabilize physical properties, homogenize

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composition, and increase energy density. Maximizing system performance therefore depends on a quantitative assessment of pre-treatment intensity and feedstock-specific optimization of conversion conditions, with particular attention to operational efficiency and downstream environmental impacts.

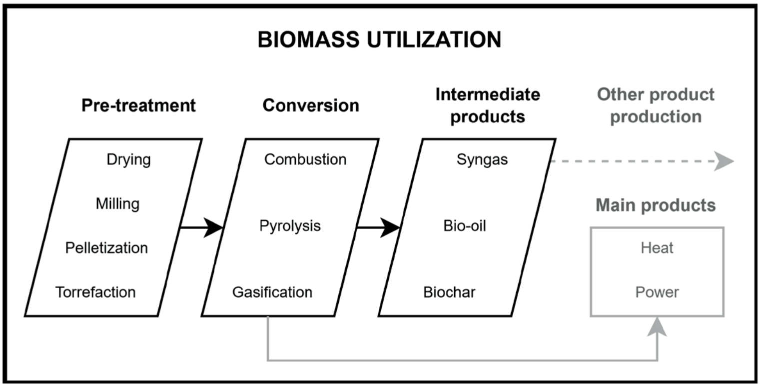

Fig. 1. Principal scheme of biomass utilization system boundaries, highlighting the sequential relationship between pre-treatment, conversion, and intermediate product formation.

Effective deployment depends on a rigorous assessment of pre-treatment needs and intensity, together with specific configuration of the chosen conversion technology and subsequent process optimization. The purpose of this study is to explore how such questions of process configuration, pre-treatment optimization, and performance improvement can be addressed through process modelling in *Aspen Plus*. By analysing available literature and selected case studies, the authors aim to determine to what extent *Aspen* software functionality can reproduce the behaviour of biomass pre-treatment and conversion systems, and which parameters of biomass and pelletisation should be incorporated for reliable and transferable simulation results.

1.1. Biomass Conversion Technologies and Products

Besides conventional biomass combustion, thermochemical conversion pathways are widely applied to generate heat, power, and intermediate energy carriers such as biochar, bio-oil, and synthesis gas (syngas) [5]. Biochar and syngas are created in gasification and pyrolysis processes, while pyrolysis also produces bio-oil. Syngas can be processed into more valuable products, like hydrogen, methanol, dimethyl ether, and other chemical feedstocks [6]. These processes operate in oxygen-limited environments at elevated temperatures. Gasification typically proceeds under sub-stoichiometric oxygen or steam conditions and can be conducted at atmospheric or elevated pressures. Pyrolysis takes place in the near absence of oxygen and is generally performed at atmospheric pressure. Feedstocks with low moisture content are preferred, since excess water reduces thermal efficiency and slows conversion kinetics. Operating temperatures vary by technology. Gasification commonly spans roughly 500–1000 °C, depending on the gasifying agent and reactor configuration. Pyrolysis encompasses multiple regimes defined by residence time, including slow, fast, and flash pyrolysis, and can occur below 450 °C or exceed 1000 °C depending on process intensity and product design [7].

1.2. Biomass Pre-treatment Processes and Pelletisation Importance

The sequential pre-conversion chain, encompassing drying, size reduction, densification and optionally torrefaction, establishes a stable and homogeneous feedstock platform that underpins optimized thermochemical, biochemical, or hybrid conversion processes, thereby strengthening the entire bioenergy value chain from raw lignocellulosic material to chemical intermediates mentioned above [8]–[11].

Pre-treatment typically commences with drying, which depends on the initial moisture content, storage conditions, and intended conversion route. Common configurations include rotary drum, flash, superheated-steam and belt dryers [12], [13]. Low-temperature convective or solar drying systems are typically employed in regions with limited process-heat availability or abundant open area, allowing extended natural air-drying of biomass under ambient or mildly heated airflow conditions [14], [15].

Size reduction (mechanical comminution) follows a sequential approach: chipping reduces coarse woody feedstocks such as logs and branches into chips, shredding is used for fibrous, leafy, or herbaceous residues, and hammer or knife milling achieves the target particle size distribution (PSD) required for reactor feed or densification units [16], [17]. The screen aperture, rotational speed, and feed moisture setpoints are optimized to balance specific energy consumption, flowability, and downstream process performance.

Mechanical densification (pelletisation) has been deployed at industrial scale, integrating moisture control, thermal conditioning, and compaction pressure to consolidate fine particulate biomass into mechanically durable, dimensionally uniform pellets [18], [19]. The industry rapidly grow – only 2 Mt of biomass pellets were produced globally in 2000 [20], reaching more than 25 Mt in 2015 [21], while it was already above 40 Mt in 2020 [22]. European Union (EU) is the one of the largest producers and consumers of biomass pellets globally. However, the quantities produced and consumed by each country's pellets can make a significant difference. For example, Latvia exports up to 90 % of the pellets and consumes only 10 % locally [23]. On the other hand, the United Kingdom imports 95 % of its pellets, with domestic production accounting for only 5 % [24]. As the industry evolves, new participants are proving their viability in the global market at a relatively rapid pace. A notable example is Brazil's significant increase in biomass pellet production [25]. Pelleted biomass is predominantly produced as solid biofuel with low ash content for residential and industrial thermal applications, though smaller shares are utilized in feed formulations and specialty functional blends [26]–[28]. The design and operation of pellet production lines or integrated biorefineries require a systematic process-engineering approach, encompassing feedstock characterization, pre-treatment, densification, and quality assurance. Empirical optimization based on operator experience must be complemented by scientific and computational methods, including process simulation, energy and mass balance modelling, and mathematical optimization techniques such as linear or mixed-integer programming, to assess process efficiency, flexibility, and internal mass-energy interactions [29], [30].

Torrefaction represents the final pre-conversion thermochemical upgrading step, although it remains commercially underutilized. It involves mild pyrolysis conducted at 200–300 °C under oxygen-deficient or inert atmospheres, inducing partial devolatilization, hemicellulose depolymerization, and mass yield reduction while enhancing energy density and hydrophobicity [31]. The resulting torrefied pellets exhibit lower equilibrium moisture content, increased higher heating value (HHV), improved durability, and enhanced storage and transport stability, making them superior feedstocks for combustion, gasification, or co-firing systems [32].

1.3. Feasibility and Applicability of Biomass-related Modelling

Experimental study of each unit operation across laboratory, pilot, and industrial scales is typically costly and slow, making process modelling and simulation essential for capturing system behaviour, optimizing throughput and scale-up, and quantifying trade-offs [33], [34]. In biomass utilization, research still centres on feedstock quality metrics and thermochemical product analysis, but experiments are now systematically augmented by models that enable prediction, optimization, and design-space exploration without consuming material or time. While empirical data remains the benchmark, model results are decision-grade when they are mechanistic, parameterized with sound physicochemical properties, and validated against experiments [35], [36].

Several programs and tools are suited to this topic of research, starting with using *MS Excel*'s potential for system modelling [37] and ending with software that allows detailed modelling of the physicochemical processes of biomass. The authors have accumulated experience working with at least three modelling programs – *TRNSYS* [38], *Energy Pro* [39], and *ANSYS Fluent* [40], [41]. *TRNSYS* is one of the most popular programs for dynamic simulation of energy systems [42]. The main advantage of *TRNSYS* is integrating accurate weather data (e.g., solar radiation and incidence angle) into the model. Its modular approach allows the modelling of individual biomass boiler systems, combined with another renewable energy source technology [43] or energy storage mechanism [44]. By studying the potential for biomass use in energy sector across different systems, the software allows for the identification of optimal operating conditions [45]. *TRNSYS* also allows seasonal fluctuations to be analysed, which is essential when biomass is used as the primary source of thermal energy. *EnergyPRO* provides an opportunity to conduct research in both technical and economic fields [46]. The software has been widely used in both industrial and academic environments for a number of benefits [47]. It allows for modelling energy systems consisting of today's typical energy sources or combinations thereof (e.g., biogas and biomass), assessing their long-term performance and profitability [48], [49]. This approach is constructive in assessing scenarios for developing the energy system at the company and national levels [50]. *EnergyPRO* makes it possible to compare the current situation based on historical data with predictable results, such as changing the natural gas boiler to a biomass boiler. *ANSYS Fluent* is widely used for modelling processes related to biomass utilization by simulating heat/substance transfer and aerodynamic flows in specific geometries [51], [52]. There are different approaches to analysing the biomass combustion process, which can predict the temperature in the furnace [53], the layout of flue gas routes [54] and chemical compounds [55]. The results obtained may be used as the improvement of the structural elements of the equipment or the optimization of operation modes, depending on the purpose of application. The main disadvantage of *ANSYS Fluent* in the context of biomass combustion modelling is the need for manual input of all stoichiometry, as there are no premade solutions in the software database.

To extend the scope of modelling beyond system-level and combustion-focused tools, it is essential to include a process simulator capable of representing full thermochemical conversion and plant-scale integration. The authors found another program suitable for biomass-related processes modelling during the primary literature analysis, which is ideal for exploring different scale technological processes and conducting economic analysis – *Aspen* software. The *Aspen Plus* is part of the *Aspen* software, which allows thermochemical transformations of biomass to be modelled. This program is indispensable if, e.g., the temperature dependence of the amount of biochar produced by pyrolysis need to be investigated [56]. In the biomass combustion model, it is possible to simulate the composition of the flue gas depending on the quality characteristics of the biomass, as well as to carry out studies regarding flue gas treatment or emission reduction [57]. *Aspen* software integrates two additional modules for economic and environmental analysis. The financial analysis takes place in the *Aspen Process Economic Analyzer* (*APEA*) sub-program, which allows the viability of the plant modelled in the *Aspen Plus* module to be assessed. On the other hand, environmental analysis can be used for emission management to evaluate and reduce the plant's direct (Scope 1) and indirect (Scope 2) emissions.

The authors have combined bibliometric analysis with the literature overview to identify trends in the use of *Aspen* software for biomass utilization. Authors found that the least represented topic in the literature is biomass pelletisation, suggesting a promising direction for future research. To explore this gap, the authors demonstrate the potential of *Aspen* software for biomass pelletisation by presenting examples of how it has been used to assess and improve the functionality of pellet production plants. This overview lays the theoretical foundation for further study, in which the authors conduct original research using *Aspen* software.

2. General Overview of the Use of the Aspen Software on Topics Related to Biomass Utilization

2.1. Trends of Use of Aspen Software in Biomass-related Studies

Researchers frequently apply bibliometric analysis to identify and quantify emerging trends within scientific domains [58]. The performance analysis component assesses publication and citation patterns over time, enabling the evaluation of research productivity and influence. To ensure reproducibility, this requires the careful selection of a scientific database and well-defined search criteria such as keywords, publication years, document types etc. Complementarily, scientific mapping is employed to visualize collaboration networks, thematic relationships, and knowledge structures, including co-authorship links among countries or institutions. In this study, both performance and scientific mapping analyses were performed using bibliographic data extracted from the Scopus database, following the methodological framework established in previous works [40], [59]. The overall approach used for data collection is summarized schematically in Fig. 2. Authors identified primary and secondary keywords groups related to biomass utilization and modelling. The primary keywords group is based on biomass quality improvement technologies, biomass processing capabilities in the energy sector, and intermediate products. The secondary keywords group consisted of terms related to the models created and applied in *Aspen* software.

A total of 1292 articles were found (see Fig. 3). Most of the studies related to processing technologies focus on gasification (35.7 %). Mutlu and Zeng describe the possibilities of using Aspen on gasification-related issues sufficiently widely [60]. Pyrolysis (7.4 %) and direct combustion (5.7 %) are less studied. In the case of intermediate products, the use of syngas is most investigated (33.1 %). A promising direction is the utilization of bio-oil (6.7 %). Studies also explore the potential of using biochar as an energy source with high calorific value (5.7 %). At the same time, only 1.5 % focus on pelletisation, and 0.5 % on torrefaction. Among pre-treatment processes, drying is most often studied (3.3 %), whereas modelling of size reduction is encountered less frequently (0.5 %).

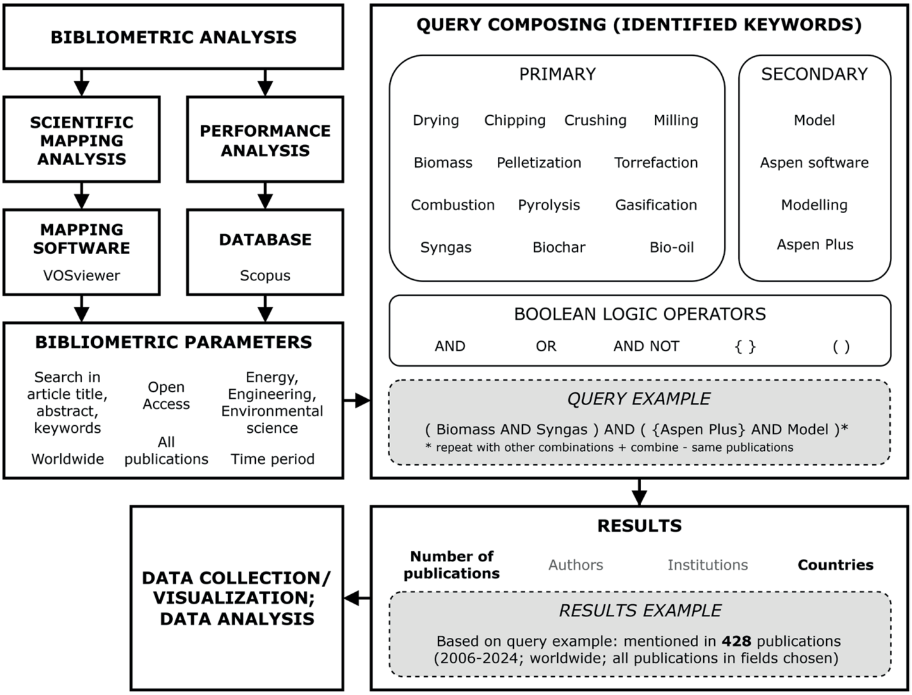

Fig. 2. Methodology used to conduct performance analysis of Aspen software trends in biomass utilization context.

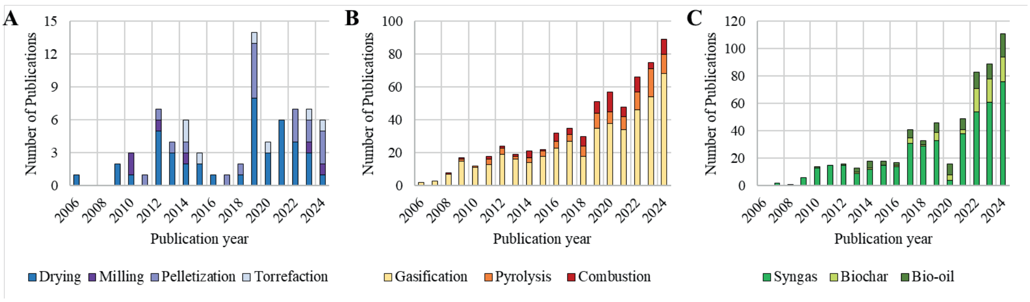

Fig. 3. Bibliometric analysis of the occurrence of pre-treatment processes (A), conversion technologies (B), and intermediate products (C) in publications utilizing Aspen software.

The trends in the number of modelling-based publications addressing biomass conversion technologies and their intermediate products indicate a steadily increasing scientific interest in this research direction. The bibliometric results also reveal there has been a sharp rise in studies on gasification, pyrolysis, and their main intermediates (particularly syngas) whereas models focusing on pre-treatment processes remain comparatively scarce. Mutlu and Zeng describe the possibilities of using Aspen on gasification-related issues sufficiently widely and concluded that most models begin with an already prepared feed, represented as a single nonconventional solid component with defined proximate and ultimate analysis, while pre-treatment is assumed rather than explicitly simulated [60]. Pre-treatment appears only indirectly, through sensitivity analyses on parameters such as feed moisture or ash content, but is not treated as a distinct process stage. Nevertheless, independent studies [61], [62] clearly emphasize that pre-treatment is critical step for transforming heterogeneous biomass into a homogeneous, energy-dense fuel with favourable logistical and combustion characteristics. Nearly all models pursue the same fundamental objective – the production of heat and electricity. This persistent discrepancy between the recognized importance of pre-treatment and its simplified representation in most simulation studies provides the rationale for the following research focus: a detailed investigation of pelletisation and other pre-treatment stages through advanced Aspen-based modelling approaches.

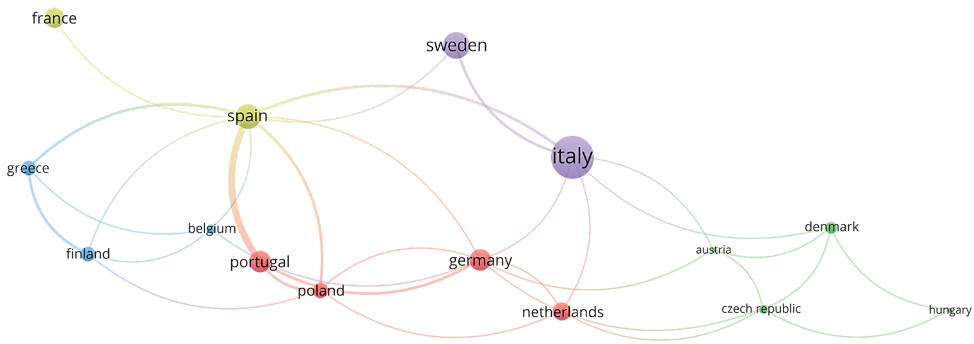

Fig. 4. Country co-authorship map of biomass utilization studies using Aspen Plus.

The co-authorship bibliometric data from all retrieved publications were subsequently used for scientific mapping analysis, enabling the visualization of collaborative relationships among countries. The VOSviewer co-authorship network (Fig. 4) reveals clear regional clustering among EU countries engaged in biomass utilization systems modelling in *Aspen Plus*. The size of each node reflects publication volume, while the connecting lines indicate the strength of international collaboration. Distinct research clusters emerge, illustrating how scientific cooperation aligns with both geographic proximity and shared thematic priorities within the European bioenergy landscape. The largest and most interconnected nodes – Italy and Spain – serve as central hubs linking multiple collaboration networks. Spain strong ties with Portugal, Greece, Poland, France, and Finland form a Southern–Western European research axis, primarily focused on the thermochemical conversion of agricultural residues, particularly gasification and pyrolysis modelling using *Aspen Plus*. A Western–Central European cluster, represented by Germany, the Netherlands, Poland, and Portugal, reflects collaborations traditionally active in combined heat and power, waste-to-energy, and process-integration modelling. The Nordic–Central–Eastern cluster, composed of Denmark, Austria, the Czech Republic, and Hungary, represents a group of countries actively involved in collaborative EU and IEA Bioenergy research initiatives. Denmark and Austria stand out for their established industrial and research infrastructures in biomass gasification and torrefaction, while the Czech Republic and Hungary contribute primarily through simulation, combustion studies, and bioeconomy coordination projects. This cluster therefore reflects complementary strengths within a shared framework of EU-supported bioenergy development. Together, these clusters demonstrate how regional research alliances are shaped by EU funding frameworks and national renewable-energy strategies. The same collaborative model could be effectively applied in the Baltic region, beginning with the consolidation of research teams experienced in energy-systems modelling to strengthen cross-border cooperation and enhance visibility within the wider European bioenergy research network.

2.2. In-depth Literature Analysis on Aspen Software Application

Following the identification of overall publication trends, 13 scientific articles were selected for an in-depth literature analysis. These papers were retrieved using the same queries applied during the performance-analysis stage to ensure methodological consistency. The objective was to identify the types of biomass feedstocks and utilization pathways investigated across the selected studies, as well as to examine the data analysis approaches, mathematical methods implemented in Aspen Plus models, and the key outcomes reported. Table 1 presents a summary of these studies, distinguishing whether each conducted technical, economic, or environmental assessments of biomass utilization options in which pre-treatment was recognized as a necessary process stage and analysed either partially or in full.

TABLE 1. REPRESENTATIVE GLOBAL STUDIES EMPLOYING ASPEN SOFTWARE FOR MODELLING AND ANALYSIS OF BIOMASS-RELATED PROCESSES

Article	**Material used**	**Type of analysis**	**Property method**	**Processes involved**	**Research description**
Xu *et al*., 2018 [63]	Wood pellets	T[1]	NM[2]	Pellet gasification	Aspen Plus modelling of a biomass-to-syngas chemical looping partial oxidation process; energy balance and process optimization for high-purity syngas
Manouche-hrinejad and Mani, 2019 [64]	Pinewood chips	T	PR–BM	Drying, Torrefaction, Pelletisation	Design and simulation of an integrated drying–torrefaction–pelletisation line to produce torrefied pellets; mass and energy balance analysis and process energy efficiency improvement
Onsree *et al*., 2020 [65]	Corn residue pellets	T	RKS	Drying, Pellet torrefaction	Techno-economic evaluation of a biomass torrefaction plant utilizing flue gas as the primary heat source for pelletized agro-residues; assessment of process performance and profitability
Manochehri *et al*., 2023 [66]	Empty fruit bunch	T	RKS	Milling, Torrefaction	Optimization of the torrefaction using response surface methodology and simulation, focusing on the effects of process parameters on product quality
Kazmi *et al*., 2023 [67]	Sunflower husk pellets	T	PR–BM	Pellet gasification	Techno-economic assessment of steam/oxygen gasification of sunflower husk pellets for biohydrogen production using Aspen Plus, including sensitivity and cost analyses
Cao *et al*., 2023 [68]	Wood pellets	T	PR–BM	Drying, Pyrolysis, Gasification	Aspen Plus dual-fluidized-bed model for steam gasification with kinetic approach; optimization of hydrogen-rich syngas composition and process parameters (temperature, steam ratio, steam temperature)
Moreda *et al*., 2024 [69]	Khat waste	T	NM (IGT approach referenced)	Drying, Pyrolysis	Investigation of the physicochemical properties and pyrolysis performance of khat waste, along with Aspen Plus simulation of the pyrolysis process compared with coal to assess bioenergy potential
Yanping Zhou, 2024 [70]	Pinewood pellets	T	PENG–ROB	Pellet gasification	Co-production of biochar and syngas from pinewood pellet gasification; experimental validation and detailed Aspen Plus kinetic

Article	Material used	Type of analysis	Property method	Processes involved	Research description
					modelling with mass/energy balance and parameter sensitivity analysis
Tuntiwongwat *et al.*, 2024 [71]	Mustard husk; Empty fruit bunch; Pinewood pellets	T	PENG–ROB	Drying, Gasification	Thermodynamic equilibrium analysis of biomass gasification for hydrogen generation; evaluation of the influence of temperature, steam, and gas composition
Detchusananard *et al.* 2022 [72]	Empty fruit bunch	T, Ec[3]	RKS–BM	Drying, Milling, Pyrolysis, Gasification	Integrated drying–pyrolysis–gasification system simulation for multi-biofuel production; energy and exergo-economic optimization using Aspen Plus and cost estimation
Sarker *et al.*, 2023 [73]	Canola residue	T, Ec	PR–BM	Torrefaction, pelletisation	Simulation and full techno-economic analysis of integrated torrefaction and pelletisation for producing torrefied fuel pellets from canola residues
Ukanwa *et al.*, 2023 [74]	Empty fruit bunch; Mesocarp fiber; Palm kernel shell	T, Ec	PENG–ROB	Drying, Milling, Pyrolysis, Gasification, Combustion	Energy and economic evaluation of integrated palm-residue utilization for activated carbon and ash fertilizer production using Aspen Plus and Aspen Economic Analyzer
Kottakalathil *et al.*, 2025 [75]	Coconut shell pellets	T, Ec, En[4]	PENG–ROB	Drying, Gasification	Simulation of coconut shell pellet drying-gasification scheme; techno-economic and environmental assessment of bioenergy production including syngas hydrogen-yield potential

[1] technical; [2] not mentioned; [3] economical; [4] environmental

Conversion performance in gasification, pyrolysis, and combustion is tightly linked to how well the biomass has been prepared before it ever reaches a reactor; whenever moisture, PSD or torrefaction severity is changed, the syngas composition, HHV, char yield or flame stability move with it. Authors in [64] and [73] explicitly tune drying and torrefaction conditions and obtain markedly different pellet properties and energy efficiencies. Authors in [65] show that the viability of a torrefaction plant for agricultural residue pellets depends strongly on how effectively low-temperature flue-gas heat is used for drying. Authors in [67] and [75] report that pellet quality and co-feeding strategies influence hydrogen yield and overall process economics.

The *Aspen Plus* models in these studies also illustrate how pre-treatment is currently handled in practice. A few works place it at the centre of the analysis: authors in [64] model a complete drying–torrefaction–pelletisation line for pinewood chips, authors in [72] integrate empty fruit bunch drying and milling with downstream pyrolysis and gasification, and authors in [73] evaluate an entire torrefaction–pelletisation process from both technical and economic perspectives. In most of the other papers, however, pre-treatment appears only as a simplified front-end: a single dryer block with fixed outlet moisture, a generic milling step, or pellets treated as a given input with prescribed proximate/ultimate analysis and durability. The modelling effort then concentrates on the conversion units using specific property methods – Peng–Robinson (PENG–ROB), Peng–Robinson–Boston–Mathias (PR–BM) or Redlich–Kwong–Soave (RKS)/RKS–BM for the gas phase, and, in several cases, extending the flowsheet to techno-economic or exergo-economic assessment. This pattern shows that researchers recognise the importance of pre-treatment but seldom explore how different pelletisation or torrefaction strategies feed back into plant-scale performance.

Considering the collaboration clusters discussed at the end of Subsection 2.1, the authors conducted a targeted overview to identify institutions within the Baltic region that carry out research aligned with the thematic scope of this paper and that could potentially consolidate efforts to increase scientific visibility. Table 2 summarizes the publications in which various institutions applied or referenced *Aspen* software for studies in the environmental engineering field, with at least one participating author affiliated with a Baltic country. The range of such studies remains limited. The earliest applications of *Aspen* software in the region were published in Estonia between 2015 and 2017, primarily conducted at the Tallinn University of Technology, Laboratory of Inorganic Materials. In Latvia, only a single international publication involving *Aspen* software has been identified, authored by a researcher from the Riga Technical University, Institute of Energy Systems and Environment, published in 2021. In Lithuania, related work has been carried out by the Kaunas University of Technology, Lithuanian Energy Institute (2023), and Vytautas Magnus University (2024), including collaboration with a Lithuanian private-sector company. Over the past five years, Poland has shown comparatively stronger engagement, with researchers from the Gdańsk University of Technology, AGH University of Science and Technology, and the Silesian University of Technology actively participating in international collaborations focused on applying *Aspen* software to bioenergy and environmental process simulations.

TABLE 2. EXAMPLES OF USING ASPEN SOFTWARE IN BALTIC REGION IN ENVIRONMENTAL ENGINEERING FIELD

Co-authorship	**Research topic**	**Raw material used**	**Reference**
Latvia, Brazil	Anaerobic Digestion	Biofuel wastes	[76]
Lithuania	Autothermal reforming	Hydrogen from biogas	[77], [78]
Lithuania	Plasma steam gasification	Surgical mask waste	[79]
Lithuania, Poland	High-temperature heat pumps	Electricity	[80]
Estonia	Dissolution of $Ca(OH)_2$ and $CaSO_4 \cdot 2H_2O$ in water	Oil shale combustion ashes	[81], [82]
Estonia	Combustion	Oil shale	[83]
Estonia, Norway	Continuous feed pyrolysis reactor	Wood	[84]
Poland, Norway	Carbon capture and storage	Sewage sludge	[85]
Poland, China	Gasification	Pine sawdust	[86]
Poland, Italy	Energy recovery from gasification	Sewage sludge	[87]

International knowledge exchange and research cooperation could significantly enhance progress toward several United Nations Sustainable Development Goals (SDGs) – most notably SDG 4 (Quality Education), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action). A deeper understanding of the national research priorities, methodological approaches, and the diversity of biomass resources studied across EU enables the transfer of best practices to the Baltic region. Such collaboration would help strengthen local expertise in environmental engineering, foster regional innovation capacity, and uncover new, underexplored opportunities for joint development of sustainable bioenergy technologies.

2.3. Characteristics of the Biomass-related Aspen Plus model

Based on the bibliometric and literature analysis, it becomes evident that *Aspen Plus* functionality is well suited not only for modelling biomass conversion but also for extending the analysis toward pre-treatment and pelletisation. The intention is not to provide a general Aspen tutorial, but to distil the common modelling steps, elements, and parameters that form a consistent basis for building process models of biomass utilization chains where pre-treatment is an obligatory stage. A more detailed theoretical and practical basis for modelling and simulating chemical processes can be found in the analysis and simulation books like "Analysis and Simulation in Chemical Engineering" [88] and "*Aspen* Plus: Chemical Engineering Applications" [89].

In Aspen Plus, every process model can be viewed as consisting of a component description and a flowsheet description. The component section specifies the substances present in the system and the methods for evaluating their thermophysical properties, whereas the flowsheet section defines unit operations and stream connections. For thermochemical biomass conversion, the component set typically combines conventional components (gases and simple compounds) with one or more non-conventional solids representing biomass and ash. Conventional components (CU) are those for which physical properties are available in databanks or can be calculated from temperature- and pressure-dependent correlations; they include, for example:

- Fuel: C, H_2, O_2, N_2, S, Cl;
- Air: N_2, O_2, H_2O;
- Flue-gas: N_2, CO_2, O_2, H_2O, CO, NO_2, NO, SO_2, SO.

Biomass and ash are introduced as non-conventional components (NC). For NC solids, physical properties such as enthalpy and density are not tabulated directly but are computed from analytical characterization data. Aspen Plus provides standard analysis types for this purpose:

- ULTANAL: elemental composition of biomass (C, H, O, N, S, Cl) and ash content;
- PROXANAL: moisture, ash, volatile matter and fixed carbon content;
- SULFANAL: sulphur content (for biomass its part is usually organic).

Based on these input parameters, Aspen Plus automatically calculates several derived properties, including HHV, using the Institute of Gas Technology (IGT, 1976) correlations. If necessary, these values can be manually adjusted in the NC PROPS section. The choice of property method dictates how Aspen Plus evaluates phase equilibria, densities, enthalpies, and transport properties of the system, directly influencing the accuracy of simulations involving gasification, combustion, or thermochemical upgrading. For biomass-derived syngas and flue gases, the most widely applied cubic equations of state include:

- PENG-ROB: based on the Peng-Robinson equation generally used in biomass and synthesis gas simulations;
- PR-BM: modified Peng-Robinson method that improves accuracy in specific cases;
- RKS and RKS-BM: used for high temperature and pressure.

The default settings for *Aspen Plus* treat biomass as a homogeneous substance. A "Yield reactor" block breaks down the biomass flow into its existing elemental compounds (decomposition). The distribution is usually calculated using the dry mass calculator (Fortran) [90]. Irrespective of the type of fuel and the process of disposal, two reactor models are often used:

- "Stoichiometric reactor" block: intended in cases where reaction stoichiometry is known. Suitable for simulating moisture evaporation processes, the user can manually define the amount of evaporative moisture;
- "Gibbs Free Energy reactor" block: use the principle of minimum energy of Gibbs to determine the end products of the reaction. Appropriate in cases where the response stoichiometry is not accurately known.

A source of oxygen is required to provide combustion simulation. This can be achieved by supplying the reactor with a molar concentration of O_2 and N_2. The outflow from the reactor should be treated as the total flow of combustion products; it includes the temperature in the furnace, the composition and volume of the flue gas, and the amount of ash. The ash is not automatically separated from the typical flow, nor is the bottom ash and fly ash ratio calculated during the simulation. A separator block shall separate ash from the total flow of combustion products. In specific cases where the purpose of the application is to incorporate into the simulation model any of the flue gas treatment technologies which, inter alia, act on fly ash separation (e.g., scrubber or electrostatic filter, the blocks of which also exist in *Aspen Plus*), it is possible to manoeuvre through the separator block a percentage of the ash remaining in the flue gas stream simulating the presence of fly ash. It is possible to define the PSD. In all of this, the separator block is also used to separate pyrolysis and gasification products.

3. Potential of Aspen Software to Improve the Performance of the Pellet Production

Detailed torrefaction–pelletisation studies in the literature show that changes in pellet quality indicators – moisture and ash content, volatile yield, mechanical strength and energy density – translate into measurable differences in combustion and gasification performance, including syngas composition, energy efficiency and emission profiles. The overview in Section 2 highlighted that, in most *Aspen*-based models, pelletisation itself is reduced to a simplified front-end assumption rather than a process that can be systematically optimised. This combination of evidence suggests that pellet properties are an important but still weakly quantified lever for improving plant-scale performance, especially when alternative or low-quality biomass (LQB) is introduced into the fuel mix. Against this background, the next step is to examine how *Aspen* software can be used to represent the key stages of pellet production and to test improvement options under realistic industrial conditions. The process of pellet production generally includes biomass collection, initial size reduction, drying, further comminution to the required fraction (milling), and densification (pelletisation). These steps can be configured in different ways depending on plant scale and available infrastructure, and must remain flexible under changing geopolitical and climatic conditions [91], [92]. Using a one specific Latvian wood-pellet plant as a reference system, the following subsections therefore formulate and qualitatively assess three *Aspen*-based improvement scenarios: (1) introduction of LQB to increase feedstock sustainability, (2) optimization of the existing cogeneration unit, and (3) integration of torrefaction to enhance pellet calorific value.

The main focus of Scenario (1) is on the pre-treatment stage of LQB (see Fig. 5). There are experimental studies demonstrating the high potential of LQB for the production of industrial fuel pellets [93], [94]. Given that literature conclusions mostly suggest the formation of a LQB mixture with wood chips or dust, additional flow is possible in this scenario. The main objective is to ensure that the new raw material can be processed on the existing production line without significant changes in the technological process. Technical analysis with the application of the *Aspen Plus* program in this scenario involves mechanical processing units. By combining sieving and crushing blocks, it is possible to predict required capacities depending on the different characteristics of the biomass. Optional is a mixer block that allows the preparation of a homogeneous biomass stream with different proportions of wooden biomass and LQB. As part of this scenario, an economic analysis with the *APEA* can explore how the use of LQB affects the total costs of the plant, which is essential when it comes to adapting to an existing market situation.

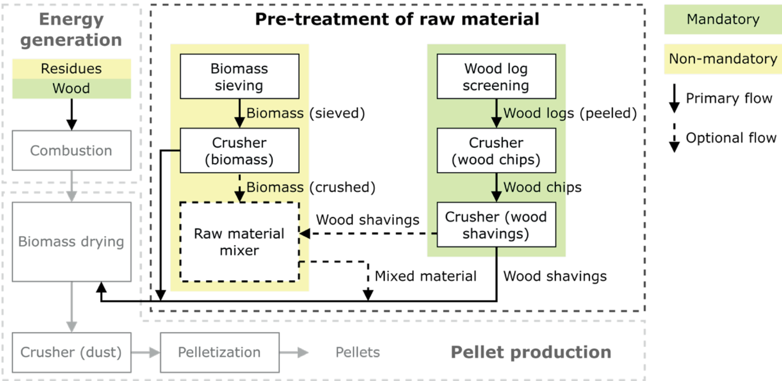

Fig. 5. Low quality biomass adding for production facility sustainability improvement.

At the selected case-overview plant, there is a cogeneration unit that primarily generates electricity for the technological process. The heat generated is used to dry LQB. In Scenario (2) the energy generation stage (Fig. 6) may be studied using *Aspen Plus*. As biomass quality changes, it is important to ensure an efficient combustion process by adjusting fuel and air ratio and that emission limit values are not exceeded. *Aspen Plus* makes it possible to predict the composition of the flue gas, the amount of heat produced and the parameters of the steam heating/cooling cycle depending on different variables. Knowing the fly and bottom ash distribution, it is also possible to model particle separation with three technologies – cyclone, wet scrubber and electrostatic filter. As far as the program is concerned, modelling chemical reactions, it also provides the possibility of forecasting the separation of gaseous compounds contained in flue gases (e.g., by desulphurization method).

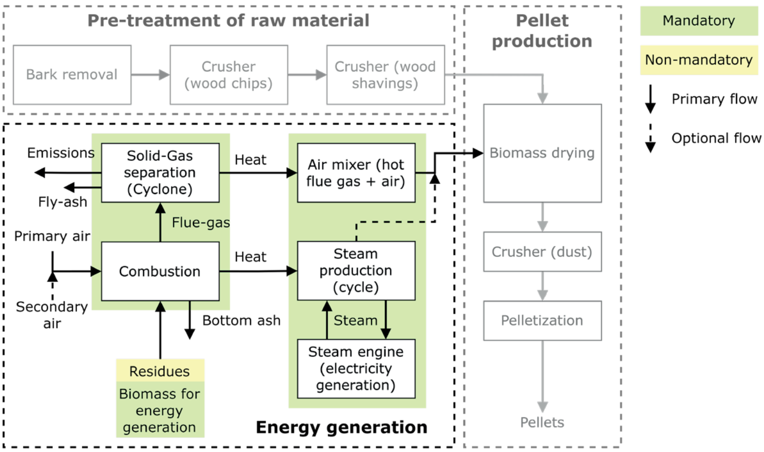

Fig. 6. Cogeneration plant performance improvement.

Scenario (3) refers to the pellet production stage. *Aspen Plus* involves modelling the drying process with different types of dryers (e.g., belt and rotary) and pelletisation. Based on the range of studies covered by this article, torrefaction of pellets produced may result in improved product quality indicators (Fig. 7).

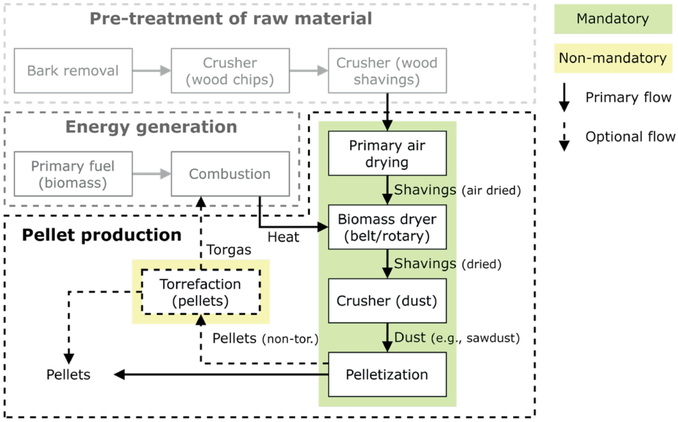

Fig. 7. Torrefaction integration for product calorific value improvement.

Torgas can be used as an additional energy source. Based on ambiguous conclusions from individual studies on the viability of torrefaction, *APEA* may be suitable for assessing its economic potential based on best practice examples.

4. CONCLUSION

The results of the bibliometric and literature analyses confirm that biomass pre-treatment is not a peripheral operation but a controlling factor in the efficiency and stability of thermochemical conversion systems. Drying, size reduction, torrefaction, and densification collectively determine reactor hydrodynamics, reaction kinetics, energy integration potential, and the quality of gaseous and solid products. Despite this recognition, pre-treatment remains only superficially represented in most Aspen-based models. The reasons are threefold:

- industrial dependence on empirical, equipment-specific know-how rather than open, model-based process design;
- the inherent variability of biomass and its strong dependence on regional conditions;
- the historical concentration of research on conversion-unit optimization rather than feedstock conditioning.

This gap limits the predictive capability of current simulations and constrains the transferability of results between feedstocks and facilities.

Within this context, the present work identifies a clear opportunity to extend *Aspen Plus* functionality toward explicit representation of pelletisation and upstream preparation steps, allowing quantitative coupling between feedstock quality and downstream process efficiency. Such an approach could bridge laboratory characterization, process design, and plant-scale optimization within a unified modelling environment.

The scientific mapping further reveals that European collaboration in *Aspen*-related biomass modelling is concentrated in Southern, Western, and Central Europe, with Italy and Spain acting as core nodes in the continental research network. The Baltic region, by contrast, remains underrepresented, although individual strengths exist – process simulation in Estonia, system-level modelling in Latvia, and thermochemical experimentation in Lithuania. Coordinated regional cooperation could therefore create a Baltic modelling cluster capable of contributing to EU-level research programs, advancing Sustainable Development Goals (SDG 4, 7, 9, and 13), and fostering the development of adaptive, feedstock-specific pre-treatment and pelletisation models for Northern European conditions.

The applied case-overview scenarios show that *Aspen Plus* can be used not merely as a theoretical simulator but as a process-engineering platform that links pre-treatment design, energy integration, and product performance. Scenario (1) illustrates the capacity to evaluate LQB co-feeding under industrial constraints. Scenario (2) shows the feasibility of combustion and heat-cycle optimization through process-parameter tuning. Scenario (3) highlights the potential of torrefaction integration for product upgrading and energy recovery. These results underline that the combined technical, economic, and environmental analysis available in both *Aspen Plus* and *APEA* provides a credible route toward data-driven optimization of pellet production systems and their integration within sustainable bioenergy value chains.

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