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Benchmarking Malaysia Nanocellulose Commercialisation with Japan

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ABSTRACT
The global market for nanocellulose is witnessing steady growth with increased investment and collaboration among research institutions and industries. Owing to its abundant lignocellulosic biomass, Malaysia can produce nanocellulose as a sustainable, renewable, biodegradable, and high-performance value-added product. However, commercial exploitation of nanocellulose in the country is limited. This research aims to evaluate the current state of nanocellulose commercialisation in Malaysia and conduct a strategic benchmarking study of leading companies in the field. A face-to-face survey was conducted with companies utilizing nanocellulose, using a structured questionnaire. This paper presents the key performance indicators (KPIs) derived from a competency analysis of the top Japanese nanocellulose industry players. The benchmarking results highlight critical KPIs, including raw-material sourcing, logistics efficiency, equipment availability, product competence, and industry acceptance. These findings provide valuable guidance for the development of the nanocellulose industry.

Keywords: *Nanocellulose industry, benchmarking, commercialisation, success factors*

Paper type: Research paper

1. Introduction

Nanocellulose has attracted tremendous research attention owing to its unique physical, mechanical, and optical properties. This is because global economic development faces a significant challenge to reduce dependency on fossil resources and address climate change issues in many areas such as food, agriculture, and energy. The use of nanocellulose could offer a solution to the disposal issues created by fuel-based products. Given climate change, sustainable and bio-based products, including nanocellulose-based products, could become the most favored alternatives to non-sustainable products related to carbon

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sequestration. The growing number of patent applications each year reflects the industry interest in nanocellulose on a global scale. More than 4,000 documents about nanocellulose were gathered between 2010 and 2017 (Charreau et al. 2020), and 1,952 patents were found in a patent survey between 2011 and 2023 (Garcia et al. 2024).

The numbers show that innovation in nanocellulose has progressed over the last decade. However, the commercialisation phase is relatively slow in some countries. Recent statistics show that worldwide production of natural lignocellulosic biomass is estimated to be 181.5 billion tons annually, of which only about 5% is reported to be used. Of this 5%, most biomass (85%) is available from forests, agriculture, and grasses, while the remainder comes from agricultural residues (Ashokkumar et al. 2022). For instance, in Malaysia, government support through the Ministry of Science, Technology, and Innovation (MOSTI) is available through various funding mechanisms to embark on this area, which offers up to the pilot and commercialisation phases. Malaysia has abundant lignocellulosic biomass that can be converted to nanocellulose as a new sustainable, renewable, biodegradable, and high-performance value-added product. The presence of lignocellulosic biomass such as agricultural residue (oil palm empty fruit bunch/frond/trunk, rice straw), wood pulp, kenaf, forestry thinning waste, and industrial waste in the country is ample to create a new cellulose-based industry that could lead to new revenue generation and provide jobs to local society. However, there is limited knowledge regarding the commercial use of nanocellulose in Malaysia. This study explores the current applications of nanocellulose in Malaysian industries and examines the commercialisation efforts underway. A benchmarking assessment compared the Malaysian nanocellulose industry with Japan, identifying gaps and opportunities for commercial adoption by relevant stakeholders in Malaysia.

2. Literature Review

A. Theory of Benchmarking

The concept of gaining competitive advantage through performance measurement and assessment, commonly known as benchmarking, remains one of the most actively promoted and utilized practices across the business and management disciplines (Meng & Karthikeyan, 2020). Benchmarking is broadly recognized as a systematic, continuous process of evaluating and identifying best practices that drive superior performance by comparing key operational metrics with those of industry leaders or peers (Lnenicka et al., 2021; Srbinoska et al., 2023). The fundamental aim is not merely to replicate but also to understand and adapt practices that can lead to measurable improvements.

Modern interpretations of benchmarking have evolved significantly beyond comparative evaluations. Today, benchmarking is widely recognized as a strategic learning and innovation tool (Sawe et al., 2023). Organizations increasingly use benchmarking not only to identify performance gaps, but also to stimulate continuous improvement, anticipate market trends, and drive strategic planning. One emerging concept is "lead benchmarking, " a predictive, future-oriented form of benchmarking that moves away from historical comparisons and focuses on forecasting and positioning for future competitiveness (Hein et al., 2019). In dynamic, technology-driven industries, this approach ensures that benchmarking remains relevant even as business environments change rapidly.

The benchmarking process generally begins with identifying a specific subject or area of interest, establishing baseline performance data, and setting measurable objectives. Organizations then select appropriate peers or industry leaders as references, often employing tools such as Data Envelopment Analysis (DEA) or other resource classification models to ensure fair and relevant comparisons (Lnenicka et al., 2021). Data collection focuses on quantifiable metrics, such as resource consumption, productivity rates, energy efficiency, and innovation outputs related to processes, products, or services (Srbinoska et al., 2023).

Following data collection, benchmarking activities proceeded to identify performance gaps and the root causes of inefficiencies. This phase often triggers the adoption of best practices through "bench learning" and "bench action" stages (Sawe et al., 2023). Importantly, benchmarking also facilitates the setting and refining of Key Performance Indicators (KPIs), serving not only internal monitoring but also external validation for regulatory, certification, and market-positioning purposes. Thus, benchmarking offers a robust multidimensional foundation for driving both operational excellence and strategic transformation.

B. Benchmarking Nanocellulose Commercialisation

Nanocellulose, a high-potential renewable nanomaterial derived from biomass, has attracted global attention owing to its exceptional mechanical properties, biocompatibility, and environmental sustainability (Bashir et al., 2022; Hanum et al., 2023). It has promising applications in industries such as packaging, pharmaceuticals, biomedicine, cosmetics, textiles, and electronics, positioning it as a pivotal material for an emerging bioeconomy. Given its wide-ranging applications, benchmarking within nanocellulose research and commercialisation has become crucial for navigating technological choices and market pathways.

Benchmarking efforts in this field often focus on comparing mechanical, chemical, and enzymatic production technologies. Mechanical methods, such as high-pressure homogenization or ultrasonication, are widely adopted, but are known for their high energy consumption and scalability issues. Chemical methods involving acid hydrolysis yield high-purity nanocellulose but raise significant environmental and waste management concerns. Recently, enzymatic approaches have gained traction, in which lytic polysaccharide monooxygenases (LPMOs) and xylanase enzymes are used to pre-treat cellulose, enabling energy-efficient and eco-friendly production (Tong et al., 2022; Sharma et al., 2023).

Benchmarking these methods is crucial, as it allows researchers and industries to conduct trade-off analyses, such as balancing yield, cost, energy efficiency, environmental impact, and scalability. Strategic comparisons inform decisions regarding which production pathways are most viable for industrial scaling and commercialisation. Such analyses are particularly important because no single method universally outperforms the others across all criteria; thus, context-specific benchmarking is vital.

Despite the surge in nanocellulose research, commercialisation has lagged behind the scientific advances. Wu et al. (2019) noted that while new nanocellulose-based products have been introduced, particularly in the composites, packaging, and personal care sectors, the actual global production volume was modest (under 40,000 tons in 2018), predominantly limited to low-value markets such as paperboard. Ciriminna et al. (2024) further emphasize a persistent mismatch between optimistic market forecasts and actual market performance. This "commercialisation gap" indicates that technological readiness alone is insufficient; strategic partnerships, value chain development, and supportive policies are equally critical. Moreover, Yi et al. (2020) highlight persistent barriers, such as high energy requirements, production costs, and industrial scaling challenges, indicating that process innovations must continue alongside market-building efforts.

C. Accelerating Nanocellulose Commercialisation in Malaysia

Malaysia, endowed with vast lignocellulosic biomass resources from its palm oil, forestry, and agricultural sectors, holds tremendous potential as a regional leader in nanocellulose production. Lignocellulosic biomass represents the world's most abundant organic feedstock, with an estimated global availability exceeding 200 billion tons annually (Singh & Verma, 2019, Abdul Khalil et al., 2020; Rashid et al., 2022). For Malaysia, valorizing this biomass into high-value nanocellulose strongly aligns with national bioeconomy goals and sustainable development agendas.

However, effective commercialisation is contingent upon overcoming significant technical and structural challenges. Among these is the recalcitrance of lignin, a complex polymer that encases cellulose fibers and impedes efficient extraction. Current extraction methods often involve intensive chemical or energy inputs, rendering large-scale production economically and environmentally unsustainable (Rashid et al., 2022). Consequently, there is growing emphasis among Malaysian research institutions on developing green pretreatment methods, including enzymatic hydrolysis and mild chemical treatments, to lower environmental impacts and reduce costs (Hanum et al., 2023).

Strategic benchmarking of international best practices has become a critical enabler in this context. By systematically comparing Malaysia's emerging production technologies, business models, and market development strategies against global leaders, stakeholders can identify gaps, opportunities, and localization strategies. This will allow Malaysia to advance its capability development, rather than duplicate less-suited models. Strategic investments in pilot plants, certification standards, market education, and public-private partnerships are essential for Malaysia to transform its biomass resources into a sustainable competitive advantage within the global nanocellulose value chain.

3. Research Design

A. Research context

The benchmarking methodology framework outlines a structured process beginning with the creation of strategic objectives, which typically specify the level of benchmarking to be conducted, whether at the corporate, divisional, or departmental level (see Figure 1). This initial stage also included the identification of relevant stakeholders and data sources. A set of metrics comprising both operational and financial indicators was selected to align with the defined strategic objectives. These metrics incorporate key performance indicators (KPIs) that fulfill the SMART criteria: specific, measurable, achievable, relevant, and time bound. Examples of measurable quantitative and qualitative information include sales volume, production cost, innovation adoption, and market reach. Benchmark performance gaps were subsequently determined based on the selected metrics and KPIs.

Following the benchmarking study, it is crucial to develop organizational capabilities across people, processes, and technologies that directly correlate with the key metrics identified. A model of operational excellence is then formulated by integrating the most impactful capabilities into an aligned management system, ensuring that R&D and innovation (R&D&I) activities are strategically connected to performance objectives. Finally, continuous improvement is achieved through the iterative process of measuring, validating, and refining strategic goals and leveraging insights gained from benchmarking efforts.

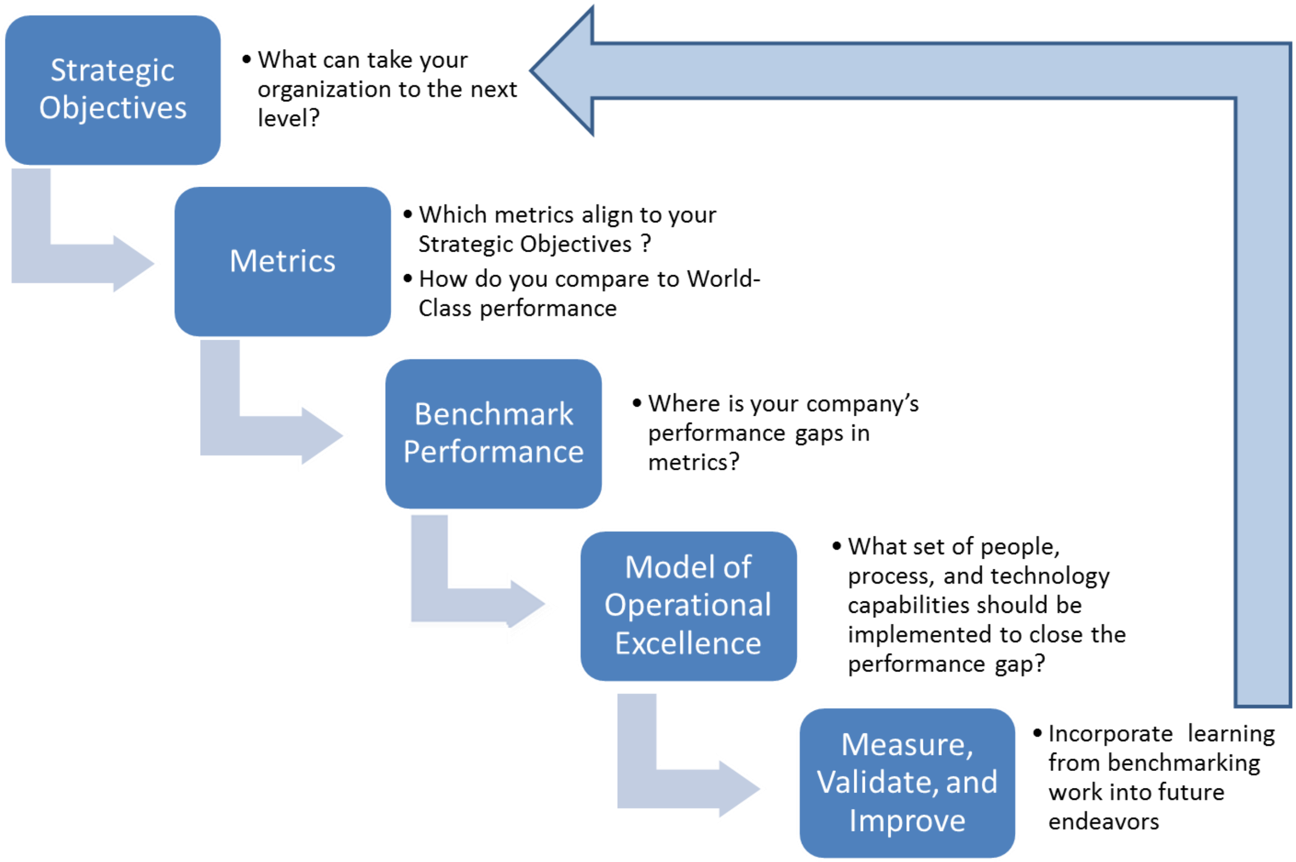

Figure 1. Framework of benchmarking methodology
Source: Adapted from Camp (1989) and quoted from Riva A. and Pilotti (2019).

To better contextualize and structure the benchmarking process, this study also adopted Porter's Value Chain framework (Figure 2), which helps map how value is created across a company's operations. Porter's model categorizes a firm's activities into primary (e.g., inbound logistics, operations, outbound logistics, marketing, and services) and support (e.g., procurement, technology development, human resource management, and firm infrastructure) activities (Ovidijus, 2023).

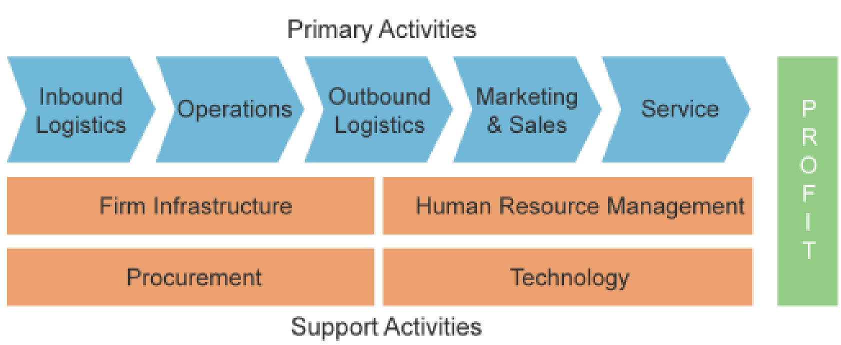

Figure 2. Porter's Value Chain Model
Source: Adapted from Ovidijus (2023)

In this study, the identified KPIs were aligned with these value chain activities to assess how each nanocellulose company generates value, and where performance gaps exist. For instance, raw material sourcing corresponds to inbound logistics, production capacity, equipment, and R&D represent operations, while commercialisation and market reach relate to outbound logistics and marketing. This integration allowed for a holistic assessment of each firm's competitive positioning along the nanocellulose commercialisation value chain.

The benchmarking activity in this study was conducted for nanocellulose companies in Malaysia and Japan. In Malaysia, companies were initially identified through secondary sources, including product listings from NanoVerify SDN. Bhd. (NVSB), and Nanostat.com. A preliminary screening survey via email and phone calls was conducted to determine which companies actively utilized or produced nanocellulose-based products. Only companies with direct nanocellulose applications were selected to participate in the face-to-face survey.

The benchmarking process followed the steps illustrated in Figure 3 and was thoroughly discussed and agreed upon during a brainstorming session among the research team, guided by an experienced industry-benchmarking expert. Strategic benchmarking was adopted as the primary approach to systematically identify and analyze world-class practices. A structured questionnaire was developed to collect data related to production capacity, R&D practices, technological capabilities, commercialisation strategies, and market applications, covering key segments along the nanocellulose value chain: raw materials, R&D&I processes, products, and commercialisation/application. The benchmarking comparison aimed to assess the competency levels and identify the performance gaps between Malaysian companies and a leading Japanese nanocellulose company. All the participating companies were informed that the information provided would be treated with strict confidential.

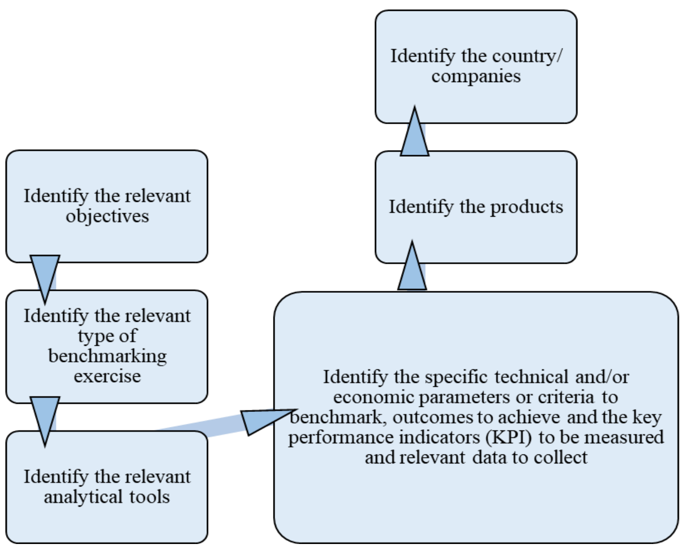

Figure 3. The benchmarking steps

B. Data collection and analysis

The data collection process consisted of two stages. First, a list of nanomaterial-based products and companies was compiled from the Malaysia's NanoVerify database. The potential nanocellulose companies were further filtered through email and telephone outreach. Companies that met the eligibility criteria were invited to participate in face-to-face structured interviews. Survey responses covered multiple dimensions, including the sourcing of raw materials, procurement practices, technological infrastructure, funding sources, commercialisation success, and market distribution strategies.

Data analysis was conducted in two parts. First, descriptive analysis was employed to characterize the current status of the Malaysian nanocellulose industry, including basic company profiles, production capacities, and market-focus areas. Second, a quantitative competency analysis was performed to benchmark Malaysian companies against Japanese ones. Competency analysis involved the derivation of KPI scores based on the survey responses. A scoring system ranging from 1 (very low) to 5 (world-class level) was applied to evaluate key performance indicators (KPIs) such as raw material sourcing, procurement process efficiency, transportation logistics, funding support, R&D collaboration, equipment availability, production capacity, product competence, quality and safety standards, commercialisation success, industry focus, and market distribution reach. Scoring levels are listed in Table 1.

Table 1. Scoring System for Key Performance Indicators (KPIs)

Score	*Performance Level*	*Definition*
5	World-Class	The company demonstrates industry-leading capabilities that align with global best practices. Operations are fully optimized, innovative, and internationally competitive.
4	High Performance	The company has advanced capabilities with reliable systems and active R&D, but still falls slightly short of world-class benchmarks.
3	Moderate Performance	The company maintains adequate operational capacity and meets industry norms. Innovation and market engagement are present but limited in scale or integration.
2	Low Performance	The company's capabilities are underdeveloped, with gaps in sourcing, R&D, production, or market reach. Infrastructure or investment may be insufficient.
1	Very Low / Nascent	The company is in an early or exploratory stage with minimal demonstrated activity or results in the evaluated KPI area. Systems may be ad hoc or informal.

Each participating Malaysian company was individually scored based on the structured interpretation of its survey data against these KPIs. The Malaysian companies' average scores were then calculated and compared to an assumed benchmark score of five, representing the performance level of the Japanese company. Gap analyses were performed to quantify the performance shortfalls, identify critical areas for improvement, and prioritize strategic development opportunities for Malaysia's emerging nanocellulose industry.

4. Results

A. Malaysia Nanocellulose Industry

NanoVerify identified 142 nanomaterial-based products that were listed from 69 companies. Of these, 41 companies responded to the initial survey, The response rate is 59% which is above the 51% average response rate in business and management and performance assessment studies (Taherdoost & Madanchian, 2024). A total of 10 companies replied yes to the question 'Do you use nanocellulose (cellulose nanocrystal/cellulose nanofibre/nanocrystalline cellulose/nanofibrillated cellulose/bacterial cellulose) in your product development? Further confirmations were conducted through either phone calls or factory visits to nine companies, one company cannot be reached because the person in charge was not around. It has been confirmed that only three companies used nanocellulose for product development. The project team managed to conduct face-to-face interviews with only two companies, as another company was unable to participate at that time due to unforeseen circumstances (Figure 4).

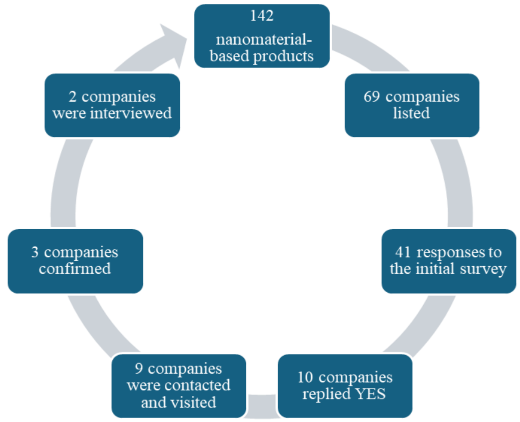

Figure 4. Identification of companies utilizing nanocellulose

These two companies are classified as micro and small enterprises, each employing fewer than 16 employees and recording annual sales below RM 15 million (SMECorp, 2024). Both companies were founded within the last decade and are entirely Malaysian-owned. In terms of technology adoption, both companies relied on external research outputs, including scientific journals, patents, universities, and research institutes. Each maintained an in-house R&D department and utilized computer-aided design (CAD) systems. Their production technologies varied between semi-automated and fully automated equipment, indicating early stage industrial capabilities. Regarding raw material sourcing, among the companies that provided information, one relied on imported nanocellulose, one relied on local sources, and one used a combination of both. The successfully commercialized products identified included face serum, oil palm biomass cellulose nanofibrils, and spray-dried cellulose nanofibrils (99.9%). Product applications spanned several sectors, including biomedicine and healthcare (face serums); construction and building composites; and paper, board, and packaging materials. Current industrial focus areas include bioplastics, plastic and nanocomposite development, pulp and paper industries, and pharmaceutical applications. In terms of market targeting, these companies serve both domestic markets (local factories and industries) and export markets (foreign consumers and exporters).

This descriptive characterization highlights the emerging nature of the Malaysian nanocellulose sector, where companies are still in the innovation and early commercialisation phases. These findings are consistent with global trends, where despite extensive research advancements, the industrial-scale commercialisation of nanocellulose remains limited because of its high production costs, scalability challenges, and market development barriers (Hanum et al., 2023; Ciriminna et al., 2024).

B. Parameters, Key Performance Indicators (KPIs), and Industry Performance

Benchmarking parameters and performance indicators were developed to assess the core competencies of the nanocellulose industry in Malaysia. These parameters were derived from a structured evaluation of the commercialisation value chain, aligned with both the benchmarking objectives and analytical tools used in the study. To structure the benchmarking process holistically, the selected parameters were aligned with Porter's Value Chain Model (Ovidijus, 2023), which categorizes firm activities into primary (e.g., logistics, operations, marketing) and support (e.g., procurement, R&D, infrastructure) functions. This approach enables an integrated assessment of how nanocellulose firms create gaps in value and capability.

Benchmarking covered four main value chain segments: (1) raw material sourcing, (2) R&D&I processes, (3) product development, and (4) commercialisation and application. These were translated into measurable performance variables, as summarized in Table 2.

Table 2. Benchmarking Parameters and Performance Variables

Parameter	Performance Variables
Raw Material	Availability and source, price, supply continuity, logistics
Process (R&D&I)	Technology adoption level, equipment, R&D collaboration, funding/investment, skilled workforce, production capacity
Products	Product competence, quality and safety standards, innovation in product development
Commercialisation & Application	Commercialisation success, marketing strategy, application potential, industry focus, distribution reach

To evaluate performance across these parameters, a structured scoring system from 1 (very low) to 5 (world-class) was applied to each key performance indicator (KPI). The survey responses from two Malaysian companies were scored using this framework. The results are shown in Table 3, reflecting the individual company scores and the national average across all KPIs.

Table 3. KPI Scores of Malaysian Nanocellulose Companies

KPI	*Company A*	*Company B*	*Malaysia Average*
Raw Material Sourcing	4	4	4.0
Procurement Process	3	4	3.5
Transportation Efficiency	3	3	3.0
Funding Support	3	4	3.5
R&D Collaboration	3	4	3.5
Equipment Availability	3	4	3.5
Production Capacity	2	3	2.5
Product Competence	2	2	2.0
Quality and Safety Control	2	4	3.0
Commercialisation Success	2	3	2.5
Industry Focus	3	3	3.0
Market Distribution	4	3	3.5

These scores reflect Malaysia's moderate capacity in upstream R&D and raw material access, but notable challenges in downstream competencies, such as production scale, product differentiation, and commercialisation success.

C. Comparative Benchmarking with Japan

To evaluate Malaysia’s nanocellulose industry against global best practices, the average national KPI scores were compared with a benchmark profile of a Japanese nanocellulose company, well-established in the pulp and paper sector, and actively commercializing nanocellulose since 2013. This Japanese firm is recognized for its integrated operations, rapid product-to-market cycles, and government-supported R&D structure. Based on survey interviews, industry reports, and recent literature, Japanese companies were assumed to perform with the highest score (5) across all KPIs (Ciriminna et al., 2024; Yano, 2024). A comparison is presented in Table 4.

Table 4. Gap Analysis: Malaysia vs. Japan Benchmark

KPI	*Malaysia Avg.*	*Japan Benchmark*	*Performance Gap*
Raw Material Sourcing	4.0	5.0	-1.0
Procurement Process	3.5	5.0	-1.5
Transportation Efficiency	3.0	5.0	-2.0
Funding Support	3.5	5.0	-1.5
R&D Collaboration	3.5	5.0	-1.5
Equipment Availability	3.5	5.0	-1.5

KPI	*Malaysia Avg.*	*Japan Benchmark*	*Performance Gap*
Production Capacity	2.5	5.0	-2.5
Product Competence	2.0	5.0	-3.0
Quality and Safety Control	3.0	5.0	-2.0
Commercialisation Success	2.5	5.0	-2.5
Industry Focus	3.0	5.0	-2.0
Market Distribution	3.5	5.0	-1.5

The largest gaps were found in product competence (-3.0), commercialisation success (-2.5), and production capacity (-2.5). These gaps suggest that the Malaysian nanocellulose industry is yet to develop robust downstream capabilities, including product innovation, market penetration, and scalable production systems. This result is consistent with the findings of Matsuoka (2023) and Yano (2024), who highlight Japan's advancements in application-specific nanocellulose development and market deployment. In contrast, Malaysia's industry remains concentrated in early stage R&D and has had limited success in transitioning to high-value commercial products.

C. Strategic Implications: Lessons from Japan and the Way Forward for Malaysia

The benchmarking findings revealed that although Malaysian nanocellulose companies demonstrate strengths in upstream areas, such as raw material sourcing and initial R&D capability, there are substantial gaps in downstream functions. These include production scalability, product differentiation, quality assurance, and commercialisation success. The limited capacity in these areas restricts Malaysia’s ability to transition innovations into market-ready nanocellulose products and hinders broader industry competitiveness.

By contrast, Japan offers a strong model for the mature nanocellulose industry. Japanese companies have engaged in the utilization of cellulose nanofibers (CNFs) for over two decades, demonstrating leadership in technological advancement and commercial applications (Romberg, 2017). In particular, pulp and paper companies have played a key role in scaling up CNF innovation. Other contributors include chemical and machinery companies that are actively engaged in downstream commercialisation (Yano, 2011). For example, Nippon Paper developed carboxymethylated CNFs and built a facility with a capacity of 30 metric tons per year to serve the food industry. The company also pioneered a cost-reduction method by producing CNFs powder. Japan’s nanocellulose is now utilized in a wide range of sectors, including automotive tires, high-performance athletic footwear, and durable food packaging such as dorayaki pancakes (Matsuoka, 2023).

These advancements are enabled by Japan’s integrated value chain, rapid product-to-market cycles (one to three years), and strong policy support for R&D and industrial innovation. Government involvement extends beyond funding; it acts as a market enabler by promoting regulatory alignment, facilitating technology transfer, and incentivizing adoption across strategic sectors. In contrast, although Malaysia’s industry exhibits pockets of competency in operations, logistics, human resources, and infrastructure, it lacks a defined core competency that distinguishes it internationally.

To close this gap, Malaysia can draw several strategic lessons from the success of Japan.

1. Establish pilot-scale production and testing facilities to accelerate the transition from research to commercialisation.
2. Incentivize public-private partnerships to foster collaboration between industry and academia in downstream product innovation.
3. Develop regulatory standards and certification frameworks for nanocellulose quality and safety, particularly for food, cosmetics, and medical applications.

4. Position nanocellulose as a strategic material within Malaysia's industrial development and green economic agendas.

Importantly, Malaysia is well positioned to lead regionally in sustainable nanomaterials because of its rich biomass base. With more than 182.6 million tonnes of biomass being generated annually, Malaysia has the potential to upcycle agricultural and forestry waste into high-value nanocellulose. Initiatives such as the Biomass Innovation Circular Economy Programme (BICEP) and the National Biomass Action Plan 2023–2030 provide a foundation for building a circular bioeconomy. Through targeted innovation, policy alignment, and industrial scaling, Malaysia can position nanocellulose as the cornerstone of its sustainability-driven industrial transformation, simultaneously promoting green growth and environmental protection.

5. Conclusion

Malaysia's nanocellulose industry exhibits significant performance gaps when benchmarked against its leading Japanese counterpart, particularly in downstream areas such as product competence, commercialisation success, and production capacity. These quantitative differences point to the structural challenges within Malaysia's innovation ecosystem. While Malaysian firms show moderate strength in raw material sourcing and basic infrastructure, the transition from research to market remains limited because of several factors: fragmented industry-academia collaboration, insufficient funding continuity, limited access to pilot-scale production facilities, and weak private sector leadership in innovation.

In contrast, Japan's nanocellulose development is underpinned by decades of sustained investment, government-facilitated public–private partnerships, and integration with established industries such as pulp and paper. This alignment enables the rapid scaling of innovations, with products typically commercialized within one to three years. Japan's nanocellulose strategy is further supported by clear quality standards, interministerial coordination, and industrial application roadmaps.

To close these performance gaps, Malaysia must undertake systemic reform. First, future research and development should prioritize translational research, moving beyond lab-scale studies toward market-ready applications, especially in packaging, biomedical, and food-contact materials. Second, policy frameworks such as the National Nanotechnology Policy 2021–2030 should be reinforced by dedicated nanocellulose funding mechanisms, tax incentives, and regulatory infrastructure (e.g., testing and certification centers) to build investor confidence. Third, industry collaboration must be scaled through co-funded R&D projects, industry-university consortia, and participation in international nanomaterial platforms.

Finally, the development of biomass-based supply chains, supported by initiatives such as BICEP, can lower input costs and enhance sustainability. By addressing these structural and institutional limitations, Malaysia could transform its biomass advantage into a competitive nanocellulose industry. Future studies should also explore economic feasibility assessments, life cycle analyses, and market demand modelling to support long-term commercialisation strategies.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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References

Abdul Khalil, H. P. S., Bhat, A. H., Ireana Yusra, A. F., & Jawaid, M. (2020). Green composites from sustainable cellulose nanofibrils: A review. Carbohydrate Polymers, 248, 116776. https://doi.org/10.1016/j.carbpol.2020.116776

Ashokkumar, Veeramuthu, Radhakrishnan Venkatkarthick, Shanmugam Jayashree, Santi Chuetor, Selvakumar Dharmaraj, Gopalakrishnan Kumar, Wei Hsin Chen, and Chawalit Ngamcharus Rivichai. (2022). "Recent Advances in Lignocellulosic Biomass for Biofuels and Value-Added Bioproducts - A Critical Review." *Bioresource Technology* 344 (PB): 126195. https://doi.org/10.1016/j.biortech.2021.126195.

Bashir, O., Rashid, S., Masoodi, N., Khan, S. A., Majid, I., Malik, M., Beenish, B. (2022). 5 - Nanocellulose: Chemistry, preparation, and applications in the food industry. In *Industrial Applications of Nanocellulose and Its Nanocomposites* (pp. 155–177). Elsevier. https://doi.org/10.1016/b978-0-323-89909-3.00008-0

Camp, R. (1989), Benchmarking: The search of industry best practices that lead to superior performance, AQQC Quality Press.

Charreau, Hernan & Foresti, Laura & Vázquez, Analia. (2012). Nanocellulose patent trends: A comprehensive review of patents on cellulose nanocrystals, microfibrillated, and bacterial cellulose. *Recent Patents on Nanotechnology.* 7. 56-80. 10.2174/18722105130106.

Ciriminna, R., Della Pina, C., Angellotti, G., Pagliaro, M., Formenti, M., & Luque, R. (2024). *Fulfilling the industrial potential of nanocellulose*. American Chemical Society [Internet]. https://doi.org/10.26434/chemrxiv-2024-wsvkz

Garcia KR, Beck RCR, Brandalize RN, Dos Santos V, et al.. (2024), "Nanocellulose, the Green Biopolymer Trending in Pharmaceuticals: A Patent Review", *Pharmaceutics*, Vol. 16 No. 1, pp. 145, doi: 10.3390/pharmaceutics16010145. PMID: 38276515; PMCID: PMC10819157.

Hanum, F. F., Rahayu, A., Amrillah, N. A. Z., and Yoga Nawaki Helmi Mustafa. (2023). Utilization and extraction methods of nanocellulose: A review. JURNAL SAINS NATURAL 13(3): 107–114. https://doi.org/10.31938/jsn.v13i3.565

Hein, A., Schmid, J., & Wagner, M. (2019). Benchmarking digital transformation strategies in the manufacturing industry. Journal of Manufacturing Technology Management, 30(8), 1234–1250. https://doi.org/10.1108/JMTM-02-2019-0056

Lnenicka, M., Luterek, M., Nikiforova, A. (2021). Benchmarking open data efforts through indices and rankings: assessing the development and context of use. *Telematics and Informatics 66*, 101745. https://doi.org/10.1016/j.tele.2021.101745

Matsuoka K. (2023). In Japan, cellulosic nanofibers are left to the laboratory. https://cen.acs.org/materials/nanomaterials/Japan-cellulosic-nanofibers-look-leave/101/i12. Accessed on 05 July 2024.

Meng, N. Y. and Karthikeyan, K. (2020). ICT-Based Performance Measurement and Benchmarking *International Journal of Advanced Information and Communication Technology* 188–196. https://doi.org/10.46532/ijaict-2020036

NanoVerify. List of NanoVerified Products, available at https://directory.nanoverify.com.my/NanoVerify (accessed May 26, 2022)

Ovidijus, J. (2023). *Porter's Value Chain Analysis: Understanding how value is created*. Strategic management insights. Available at https://strategicmanagementinsight.com/tools/value-chain-analysis/ (accessed October 28, 2024)

Rashid, E. S. A., Gul, A., Yehya, W. A. H., Julkapli, N. M. (2022). Physicochemical characteristics of nanocellulose during different catalytic hydrolysis processes. Heliyon, 8(1), e07267. https://doi.org/10.1016/j.heliyon.2021.e07267

Riva, A. and Pilotti, L. (2019). "The strategy and the evolution of benchmarking methodology: the case of Rank Xerox-Fuji", *Economia Aziendale Online*, Special Issue, Vol. 10 No. 2, pp. 273-291.

Romberg P. (2017). Nanocellulose Market Development in Japan. https://blog.borregaard.com/exilva/nanocellulose-market-development-in-japan. Accessed on 05 July 2024.

Sawe, E., Kimathi, M., & Otieno, J. (2023). Strategic benchmarking practices and organizational performance in the Kenyan manufacturing sector. African Journal of Business Management, 17(2), 45–58. https://doi.org/10.5897/AJBM2023.9345

Sharma, R., Gupta, P., & Verma, S. (2023). Enzymatic approaches for sustainable nanocellulose production: a review. Carbohydrate Polymers, 297, 120050. https://doi.org/10.1016/j.carbpol.2022.120050

Srbinoska Stevcevska, D., Hristova, S., Stevkova Shterieva, M., Petkovska, S. (2023). Benchmarking as a Measure of Competitiveness in North Macedonia. *Ekonomické Rozhľady – Economic Review*, *52*(1), 4–28. https://doi.org/10.53465/er.2644-7185.2023.1.4-28

Singh, S. & Verma, J. P. (2019). *Bioethanol Production from Different Lignocellulosic Biomass* (pp. 281–300). apple academic. https://doi.org/10.1201/9780429265099-15

SME Corp Malaysia. (2024). Garis Panduan bagi Definisi PKS., available at https://www.smecorp.gov.my/images/pdf/2024/Garis_Panduan_bagi_Definisi_PKS_Mac_2024_Akhir.pdf (accessed 28 October 2024)

Taherdoost, H. & Madanchian, M. (2024). The Impact of Survey Response Rates on Research Validity and Reliability. 10.4018/979-8-3693-1135-6.ch009.

Tong, X., He, Z., Zheng, L., Pande, H., & Ni, Y. (2022). Enzymatic treatment processes for the production of cellulose nanomaterials: a review. *Carbohydrate Polymers*, *299*, 120199. https://doi.org/10.1016/j.carbpol.2022.120199

Wu, B., Wang, S., Tang, J., & Lin, N. (2019). *Nanocellulose in High-Value Applications for Reported Trial and Commercial Products* (pp. 389–409). Springer Singapore. https://doi.org/10.1007/978-981-15-0913-1_11

Yano H. (2011). Current situation of nanocellulose in Japan. https://www.tappi.org/content/events/11NANOSTDS/paper/yano.pdf. Accessed on 05 July 2024.

Yi, T., Liu, Y., Huang, L., Mo, Q., Zhao, H., Pan, D., Xu, H., Hu, B., & Song, H. (2020). From cellulose to cellulose nanofibrils: A comprehensive review of the preparation and modification of Cellulose Nanofibrils. *Materials*, *13*(22), 5062. https://doi.org/10.3390/ma13225062