Research mapping of Indonesia nano-lignocellulose fiber studies and its potential for industrial application

Achmad Solikhin^{1,2} · Agy Wirabudi Pranata³ · Tamyizul Muchtar⁴ · Shigiheko Suzuki⁵ · Yoichi Kojima⁵ · Hikaru Kobori⁵

Received: 7 October 2019 / Accepted: 2 March 2020 / Published online: 6 March 2020
© Springer Nature Switzerland AG 2020

Abstract

Nano-lignocellulose fibers (NLCFs) studies have been undertaken intensively in Indonesia because of its extraordinary properties of the nanofibers for various applications. The Government of Indonesia has also supported the development of the studies into industrial application. However, the studies about the nanofibers were still limited thereby creating barriers to the implementation of the studies into industrial application. Based on this study, NLCFs comprised lignocellulose nanofibers, bacterial nanocellulose, nanocrystalline cellulose, and nanofibrillated cellulose. From this study, empty fruit bunch of oil palm became the most studied natural fiber for NLCFs isolation, followed with other sources, such as bacteria, cassava, bamboo, and pineapple. From the Google Earth and ArcGis mapping, NLCFs studies were mostly conducted in Java Island over other Indonesia islands. The phenomenon was due to the availability of nanofibers-producing machines and its instrumentations. There has been yet no specific regulation supporting the development of NLCF studies, but there are some ministerial roadmaps and plans created to support the studies. Yet, NLCF studies have been not only concerned on its isolation and characterization but also the studies have been concentrated for exploring the NLCF potential for industrial application purposes, such as: paper making, pharmaceuticals, food and packaging, medicine, and bio-absorbent.

Keywords Nano-lignocellulose fibers · Indonesia research and initiative · Government of Indonesia · Google Earth and ArcGis mapping · Industrial application

1 Introduction

Nanotechnology research has been an interesting study topic for researchers, industries, and universities in Indonesia. In addition, the Government of Indonesia (GOI) has challenged them to conduct more studies and explorations on the potential of nanomaterials for industrial purposes. For instance, the GOI supported the

establishment of Indonesia Society for Nano (MNI) that has been successful to gather more than 300 nanotechnology experts throughout Indonesia to develop nanomaterial science and technology. Even, Indonesian Ministry of Research, Technology, and Higher Education enacted a Main National Research Plan in a period of 2017–2045 in which nanotechnology has been the main national research priority. Furthermore, In the National Research

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s42452-020-2408-x>) contains supplementary material, which is available to authorized users.

✉ Achmad Solikhin, achmad_solikhin@apps.ipb.ac.id; achmad.solikhin@asean.org | ¹Center for International Forestry Research, CIFOR Headquarters, Bogor 16115, Jawa Barat, Indonesia. ²Southeast Asian Regional Center for Tropical Biology, Bogor 16134, Jawa Barat, Indonesia. ³Halal Science Center, IPB University, Bogor 16114, Jawa Barat, Indonesia. ⁴Faculty of Forestry, IPB University, Bogor 16680, Jawa Barat, Indonesia. ⁵Faculty of Agriculture, Shizuoka University, Shizuoka, Shizuoka Prefecture 422-8017, Japan.

SN Applied Sciences (2020) 2:564 | <https://doi.org/10.1007/s42452-020-2408-x>

Plan, bio-nanomaterials; which encompass bio-fibers, cellulosic materials, and bio-composite; have been the major theme for nanotechnology research [30].

With tremendous support of the GOI, bio-nanomaterials studies are predicted to increase annually because of the excellent characteristics of nanomaterials derived from natural or biological resources and its potential application for various industries. In addition, the abundance biomass from agriculture and forestry can be another reason to the development of bio-nanomaterial studies in Indonesia. Through nanotechnology, the biomass can be explored its potential as a main source for nano-lignocellulose fibers (NLCFs). Chemical, mechanical, biological, and the combination of those methods can be harnessed to isolate NLCFs. NLCFs obtained can be divided into four categories, including lignocellulose nanofiber (LCNF), bacterial nanocellulose (BNC), nanocrystalline cellulose (NCC), and nanofibrillated cellulose (NFC). Those NLCFs forms can be easily distinguished based on its sources, isolation methods, acquired nanomaterials domain (amorphous or crystalline), deposited chemical components, nanomaterial morphology, particle size, crystallinity, and shapes [36, 40, 54].

Studies on NLCFs types were carried out intensively in Indonesia with varied sources of biomass. LCNFs were isolated from bio-fibers of OPEFB and rattan for food packaging [44] and automotive purpose [33], respectively. NCCs were mostly extracted by means of acid hydrolysis from passion fruit peel [53], cabbage wastes [4], and corn cob [16]. Besides those sources, bamboo, agave, and acacia wood were also utilized as another source of nanomaterial isolation [6, 43, 47]. In previous studies, the high purity of BNC was biosynthesized from extracellular product of *Acetobacter xylinum* bacteria [2, 3, 29].

Given the potential of the NLCFs research, NLCFs have a big opportunity to be developed for various products in Indonesian industrial applications. However, the applications are presumably hampered with limited availabilities of the relevant research. Previous research on NLCFs was only about its isolation, biosynthesis, characterization, and application for nanocomposites [5, 9, 22, 37]. Furthermore, there have not yet been some studies about the utilization of NLCFs for industrial applications although certain business initiatives were identified to use NLCFs types for their commercial products. As a result, this study was purposed to analyze previous NLCFs studies and potential for industrial applications by mapping them using Google Earth and ArcGis mapping. In addition, gap analysis between NLCFs research and its initiative development was also investigated.

2 Method

2.1 Materials and data sources

Data were obtained by means of systematic literature review from varied sources of national and international publications. All the data were in form of secondary data with sources that were from journals, thesis, dissertation, newsletters, regulations, and grey literature. All those publications, which were used to analysis, spanned from 2008 to 2019. Those publications were searched by using Google Scholar with key words of “nanocellulose”, “cellulose nanofibers”, “lignocellulose nanofibers”, “nanocrystalline cellulose”, “nanofibrillated cellulose”, “bacterial nanocellulose”, and “Indonesia”. Software of Google Earth and (Version 7.3.2.5495, Developer: Google, USA) and ArcGis version 10.3 (Developer: ESRI, Indonesia) were used to create research maps. The creation of research maps was based on the places where the NLCFs studies were undertaken.

2.2 Procedures

2.2.1 Collection and analysis of data

Acquired literature was subsequently extracted into two kinds of data, namely publications and NLCFs research information. In the publications, the data consisted of some parameters, including publication authors/co-authors, research place, research institution, year, research title, and references. In the NLCFs research information, the data comprised NLCFs types, material sources, isolation methods, final products, NLCFs properties, and nanocomposite properties. Next, those data were tabulated in an Excel spreadsheet and were then used for analysis and map creation. To ease the tabulating process; cellulose nanocrystals, cellulose microcrystals, cellulose nanowhiskers, and microcrystalline cellulose were the other names of NCC, and those were entered in a type of NCC. In addition, cellulose microfibrils, cellulose nanofibrils, and microfibrillated cellulose were classified into NFC. Furthermore, BNC consisted of bacterial cellulose, microbial cellulose, and bio-cellulose.

Prior to data analysis, a brief description about LCNFs, NCC, NFC, and BNC were provided in this manuscript with aim to educate the readers about those NLCF types. Obtained data were then analyzed based on publication/research period, research places distribution, NLCFs types, and NLCFs sources. Aside those data, regulations about nanotechnology research and industrial application, which were issued by the GOI, were used

for analyzing a gap between research and initiatives development.

3 Research mapping

Research mapping was formed to understand the NLCFs research distribution in Indonesia. Data on research places distribution were used as a main source for creating maps assisted with two supporting software. The software was Google Earth and ArcGIS version 10.3 with a purpose to determine geographical coordinate of NLCFs research places and to display the geographical sets of the sites, respectively.

4 Results and discussion

4.1 Nano-lignocellulose fibers

4.1.1 Nanocrystalline cellulose

It is not LCNFs isolation alike, NCC was obtained from cellulose continued with certain hydrolysis processes, including enzymatic hydrolysis, ionic liquid solvolysis, acid hydrolysis, or 2,2,6,6-tetramethylpiperidine 1-oxyl (TEMPO) oxidation [10, 39, 49, 52]. As an important pretreatment, pulping and bleaching are also used to reduce cementing agents (hemicellulose, lignin, and amorphous lignin), and post-treatment process that includes ultrasonication and filtration is also harnessed to produce purified NCC. NCC production requires the removal of amorphous part of lignocellulose but remains crystalline domain. As a result, shapes of whisker, needle, rod, and or spherical are the most common formation of NCC extracted by means of these above methods [27, 28]. In addition, most of NCC are also uniform and finest in its size because of the removal of less-ordered region through extensive chemo-mechanical methods with remaining crystalline domain/region. For example, Li et al. [26] researched NCC isolation via two stages, including TEMPO-mediated oxidation and formic acid hydrolysis. NCC obtained from these stages had a length range between 50 and 300 nm and a width range between 2 and 4 nm. In the above study, formic acid was used to swell cellulose fibers, to release NCC from amorphous region, and to remove hemicellulose whereas NCC surface charges were increased by means of TEMPO-mediated oxidation.

4.1.2 Nanofibrillated cellulose

Obtainment of NFC is much emphasized on defibrillation process after purifying cellulose. Defibrillation process

can disintegrate cellulose microfibrils into elementary fibrils and this process can lead to the increase exposure of surface area and hydroxyl group availability [51]. This process is also able to be undertaken by top-down approaches, which include grinding, high pressure homogenizer, high-speed blender, microfluidization, refining, cryocrushing, and ultrasonication [20]. Prior to defibrillation process, a chemical pretreatment and or enzymatic pretreatment can be utilized for cellulose extraction, such as enzymatic, carboxy-methylation, acetylation, and TEMPO-mediated oxidation [31]. The shape of NFC is distinctively featured with long, flexible, entangled or individualized, and web-like cellulose fibrils. NFC has an average diameter range between 5 and 60 nm with several micrometers in length [23, 48]. Furthermore, NFC is also very distinct with other NLCFs because this nanomaterial is still composed with alternating crystalline and amorphous domains.

4.1.3 Bacterial nanocellulose

BNC consists of high-purified cellulose with a 3 dimension and interconnected cellulose network form. This nanomaterial is biologically synthesized from aerobic bacteria through agitated/stirred and static culture method. With bottom-up approach, this BNC is uniquely different with other NLCF types. The most researched bacterium used for BNC synthesis is *Actobacterium xylinum* aka *Komagataeibacter xylinus* [12, 20]. According to Corujo et al. [11] and Jozala et al. [21], thick, entangled nanoribbon network, leather-like white pellicles are mostly featured from the obtainment of BNC from static culture method whereas irregular pellets or suspended fibers are mostly formed by agitated fermentation of BNC. BNC has a unique structure with an average length in 100 μm and an average diameter about 100 nm, and the BNC contains a bundle group of ribbons with a 2–4 nm diameter cellulose microfibril [45]. BNC has remarkable properties, such as high water holding capacity, high polymerization degree, high tensile strength, high crystallinity, and high moldability in situ [12]. Because of those properties, BNC has the potential for textile manufacturing, food and packaging industry, pharmaceuticals, and medical industry.

4.1.4 Lignocellulose nanofibers

LCNFs are isolated from lignocellulose biomass by using top-down approaches, especially via mechanical methods. The isolation remains not only cellulose but also lignin, hemicellulose, pectin, extractives, and other inorganic matters. However, chemical process—pulping and bleaching—can be added as an additional treatment for

the fabrication of LCNFs [13, 41]. Dry or wet disk milling, high speed blender, and vibrational milling are the common mechanical methods to produce LCNFs [8, 18, 24, 34]. Through those methods, LCNFs with an aspect ratio of 100 and thickness of 14–100 nm can be obtained. The shape of LCNFs can be in form of entangled individual, spherical, and uneven fibrils. Due to mechanical methods, acquired LCNFs are dominated by amorphous region over crystalline domain, leading to the decrease of crystallinity [44]. However, LCNFs can be still harnessed as a reinforcing agent for food packaging, automotive, and wood composites due to the compatibility between LCNFs and its composite matrices.

4.2 Nano-lignocellulose fibers research in Indonesia

4.2.1 Research period

There are four types of NLCFs researched in Indonesia, consisting of NCC, NFC, BNC, and LCNF. Based on the research period, there was slight increase in the studies trend of NLCFs (Table 1), indicating NLCFs has become an interesting research topic for biomaterials. Throughout the eleven five years, there was an increase trend of NLCFs studies, and that would presumably increase in the next few years. From Supplementary Data I, NCC and NFC have mounted since 2016 because those NLCF types were easily isolated with acid hydrolysis, ultrasonication, and high pressure homogenizer [4, 9, 14]. These methods also allowed to manufacture nanostructured fibers below 100 nm. However, LCNF has been the rarest research topic since the last seven years because of the difficulty to isolate nano-sized fibers below 100 nm. The presence of cementing agents (pectin, lignin, hemicellulose, and amorphous cellulose) and extractives might be the physical barriers to isolate LCNF [44]. In addition, multi-mechanical stages are required for producing LCNF as not using chemical pretreatment. That will generate high consumption of electricity and release high carbon footprint. Chemical treatments, which include enzymatic treatment and TEMPO oxidation, can be the easiest way to reduce the electricity [7]. Besides NCC, NFC, and LCNF studies, BNC has also become another interest for NLCFs research in Indonesia. Through the

additional chemical and mechanical methods, BNC was easily produced with an average diameter range between 10 and 100 nm, and a length in micrometers [1–3, 29, 42].

Table 2 Natural fibers studied for NLCF research

Sources	Types of NLCF			
	NCC	NFC	BNC	LCNF
Oil palm	23	22	0	5
Bacteria (Nata de coco)	0	0	31	0
Cassava	11	3	0	0
Bamboo	2	8	0	0
Pineapple	5	3	0	0
Banana	6	1	0	0
Water hyacinth	5	1	0	0
Cotton	4	1	0	0
Kenaf	2	3	0	0
Wood	1	2	0	1
Cotton	4	1	0	0
Ramie	2	2	0	0
Rattan	3	1	0	1
Bagasse	2	3	0	0
Corn	3	0	0	0
Advantec filter paper and avicel/cellulose	2	0	0	0
Snake fruit	2	0	0	0
Sugar palm	2	0	0	0
Sludge pulp and paper	1	1	0	0
Cabbage waste	1	0	0	0
Arenga palm	1	1	0	0
Yam fruit	1	0	0	0
Reed	1	0	0	0
Nypa	1	0	0	0
Agave	0	1	0	0
Passion fruit	1	0	0	0
Red sweet potatoes	1	0	0	0
Sago	1	0	0	0
Tofu	1	0	0	0
Sisal	1	1	0	0
Sugarcane	1	0	0	0

Table 1 Nano-lignocellulose fibers studies in Indonesia

Nano-lignocellulose fiber types	Research period					
	2008–2009	2010–2011	2012–2013	2014–2015	2016–2017	2018–2019
NCC	0	2	9	10	49	33
NFC	2	1	8	13	27	13
BNC	1	0	4	13	7	6
LCNF	0	0	1	1	2	3

4.2.2 Natural fibers used for research

Natural fibers, which were commonly used for NLCF research in Indonesia, are much diversified with a dominant source of agriculture byproducts (Table 2). However, Indonesia has much potential of natural fibers over those listed in Table 2 that can be explored more for manufacturing NLCF. From the table, oil palm becomes the most studied material, which is used for NCC, NFC, and LCNF production. That is because the material is an inexhaustible source and a biodegradable waste in Indonesia, especially in Kalimantan, Sumatera, and Java Island. According to Rahayu et al. [38], Indonesia has the potential to

generate oil palm solid waste biomass and palm oil mills effluent (POME) of about 20.07 million tons and 23.7 million tons, respectively. Nata de coco, cassava, and bamboo are the other biopolymers for the isolation of NLCF. Most of natural fibers used for NLCF studies are for NCC and NFC production over BNC and LCNF production. That occurs because NCC and NFC are easily produced by those fibers by using a simple method of acid hydrolysis and mechanical methods, respectively. In this study, BNC is synthesized from *Actobacterium xylinum* with various high-sugar media, such as coconut, soya/tofu, and pineapple. LCNF is mostly obtained from oil palm because of its abundant availability. In addition, oil palm fibers are very easily to be mechanically broken down and disintegrated into nanofibers although some of aggregations are also found during the isolation. As a result, post-treatments are needed to avoid aggregations, such as freeze-drying, solvent exchange, ultrasonication, and surfactant addition.

Table 3 Sites used for NLCF research in Indonesia

Nano-lignocellulose fibers	Research places in Indonesia				
	Java, Bali, and Madura	Sumatera	Kalimantan	Sulawesi	Papua
NCC	67	33	1	5	1
NFC	56	8	1	1	0
BNC	24	7	1	0	0
LCNF	7	0	0	0	0

4.2.3 Research places

NLCF studies were undertaken in all Indonesia islands, including Java, Bali, Madura, Sumatera, Kalimantan, Sulawesi, and Papua (Table 3). The distribution of NLCF research in Indonesia can be seen in Fig. 1. However, the

Fig. 1 Studies map of nano-lignocellulose fibers in Indonesia

studies are not obviously well-distributed; and are much concerned in Java Island; especially those are located in Jawa Barat and Jawa Tengah. Java, Bali, and Madura are the most dominated places for NLCF studies followed with Sumatera, Sulawesi, Kalimantan, and Papua. The executors of the studies are from universities and governmental research institutes (Supplementary Data 1). In Java, Bali, Madura, and Sumatera Island; NCC, NFC, BNC, and LCNF still become the subject of NLCF studies in which NCC and NFC are still the dominated research themes (Fig. 2). Those islands possess many research institutions and universities that support the development of NLCF studies. In addition, materials, machines, and instrumentations that are necessarily for isolating and characterizing NLCF are available in those islands.

From this study, there is a discrepancy between nanotechnology research and natural fibers availability. For instance, oil palm that has been the major nanomaterial isolation is abundantly available in Kalimantan but the nanomaterial research is only concentrated in Java and Sumatera. Meanwhile, BNC that is considered easily to be synthesized for nanocellulose is rarely studied in Kalimantan, Sulawesi, and Papua Island (Fig. 3). Furthermore, Papua Island is very rare for NLCF studies to reach, and only once for LCNF research has been done (Fig. 4). Aside lack of nanotechnology machines and instrumentations, those issues are presumably due to the lack of information and interests of the relevant institutions to research NLCF.

4.3 Existing nano-lignocellulose fibers regulations

The GOI has not yet issued a particular regulation that focuses on nanotechnology and NLCF research and initiatives development. However, National Standardization Agency for Indonesia (BSN) set a national standard, focusing on nanotechnology. The Indonesian National Standard (SNI) was adopted from International Organization for Standardization (ISO) publications, especially ISO/TS Technical Specification and ISO/TR Technical Reports (Supplementary Data 2). Table 4 shows that the standard consisted of four big groups, including definition, nanomaterial production, nanomaterial characterization, and nanomaterial risk evaluation. From the standard, in a group of nanomaterial characterization, SNI ISO/TR 19,716: 2016 reported the guidance for characterization of NCC, which focuses on sample preparation, measurement methods, and data analysis. Characterizations of NCC in the standard comprise chemical composition, surface functional groups, degree of polymerization, crystallinity, moisture content, contaminants, morphology, viscosity, morphology, and thermal properties. Among the other NLCF types, NCC has been a major concern in the standard because NCC is the most feasible to be commercialized for industrial

application in Indonesia. That is due to the availability of the standard that has been already in line with industrial uses. NCC is easily isolated by using chemical treatments, most notably, acid hydrolysis over other NLCFs. Furthermore, NCC is internationally traded across the countries with several sources of natural fibers.

Although the GOI has not yet determined NLCF regulations, Indonesia research agencies and universities have been propelled to explore, study, and implement NLCF potential. For example, Center for Innovation, Indonesian Institute of Sciences (LIPI) in partnership with Kyoto University has collaborated to research and develop NFC for composites application [19]. According to Haryono and Rohman [17], some universities also attempted to open nanotechnology centers providing nanotechnology instrumentations, such as: Universitas Indonesia, Bandung Institute of Technology, Gadjah Mada University, Sepuluh November Institute of Technology, and Airlangga University. To support of NLCF research and its development, the GOI has mandated Ministry of Industry and Ministry of Research, Technology, and Higher Education to create NLCF research roadmap and plan. For example, Ministry of Industry legalized “Nanotechnology Roadmap 2010–2014”, which consisted of the utilization of lignocellulose natural fibers and its application for paper industrial applications [32]. Ministry of Research, Technology, and Higher Education also created “Main National Research Plan 2017–2045” [30]. In the Main National Research Plan, nanotechnology has been clearly the main national research priority in which bio-nanomaterials, which encompass bio-fibers, cellulosic materials, and bio-composite, have been the major theme for nanotechnology research.

4.4 Potential of NLCFs research for initiatives development

In this study, NLCF were mostly used for nanocomposite films, membrane, and hydrogels with various application, which included paper making, pharmaceutical coating agent, bio-plastic, bio-foam, food packaging, table excipient, bioabsorbent, and drug delivery (Supplementary Data 1). Solvent casting is the easiest and the most reproducible method to synthesize those nanocomposite products. Lagashetty et al. [25] and Oksman et al. [35] also stated that solvent casting was one of the easiest and simplest methods to produce polymer nanocomposite because it needed simple equipment and was less time consuming. Besides the method, electrospinning, injection molding, impregnation and immersion, and atomic layer desposition are the other methods used for the obtainment of nanocomposites.

Yet, there are no producers or industries from Indonesia reported to produce NCC, NFC, BNC, and LCNF.

Fig. 2 Research distribution map of NCC **(a)** and NFC **(b)** in Indonesia

Fig. 3 BNC studies map in Indonesia

Fig. 4 Distribution map of LCNF studies in Indonesia

According to Global Market Insights [15], Indonesia is one the targeted market for marketing NLCF materials, especially NCC, NFC, and BNC. Those NLCF types

are presumably used for biocomposites, water purifier, food and beverage, oil and gas, paper processing and personal cares. Furthermore, prominent producers that

Table 4 Relevant SNI lists for NLCF based industries in Indonesia

Standard group	Title	SNI
Definition	Nanotechnologies—Vocabulary—Part 1: Core terms	SNI ISO/TS 80,004–1:2016
	Nanotechnologies: Vocabulary—Part 2: Nano-objects	SNI ISO/TS 80,004–2:2016
	Nanotechnologies: Vocabulary—Part 12: Quantum phenomena in nanotechnology	SNI ISO/TS 80,004–12:2016
	Nanotechnologies: Vocabularies for science, technology and innovation indicators	SNI ISO/TS 18,110:2016
	Nanotechnologies: Considerations for the development of chemical nomenclature for selected nano-objects	SNI ISO/TR 14,786:2016
	Nanotechnologies: Model taxonomic framework for use in developing vocabularies—Core concepts	SNI ISO/TR 12,802:2015
	Nanotechnologies: Vocabulary—Part 5: Nano/bio interface (ISO/TS 80,004–5:2011, IDT)	SNI ISO/TS 80,004–5:2013
	Nanotechnologies: Vocabulary—Part 4: nanostructured materials (ISO/TS 80,004–4:2011, IDT)	SNI ISO/TS 80,004–4:2013
	Nanotechnologies: Terminology and definitions for nano-objects; Nanoparticle, nanofibre and nanoplate	SNI ISO/TS 27,687:2011
	Nanotechnologies: Methodology for the classification and categorization of nanomaterials	SNI ISO/TR 11,360:2011
Nanomaterial production method	Nanotechnologies: Compilation and description of toxicological screening methods for manufactured nanomaterials	SNI ISO/TR 16,197:2016
	Nanotechnologies: Vocabulary—Part 8: Nanomanufacturing processes	SNI ISO/TS 80,004–8:2015
	Nanomaterials: Preparation of material safety data sheet (MSDS)	SNI ISO/TR 13,329:2015
	Nanotechnologies: Nanotechnologies – Guidance for developing representative test materials consisting of nano-objects in dry powder form (ISO/TS 16,195:2013, IDT)	SNI ISO/TS 16,195:2015
	Nanotechnologies: Materials specifications -Guidance on specifying nano-objects (ISO/TS 12,805:2011, IDT)	SNI ISO/TS 12,805:2013
Nanomaterial characterizations	Nanotechnologies: Vocabulary—Part 6: Nano-object characterization	SNI ISO/TS 80,004–6:2015
	Nanotechnologies: Characterization of cellulose nanocrystals	SNI ISO/TR 19,716:2016
	Nanotechnologies: Characteristics of working suspensions of nano-objects for in vitro assays to evaluate inherent nano-object toxicity	SNI ISO/TS 19,337:2016
	Nanotechnologies: Guidance on physico-chemical characterization of engineered nanoscale materials for toxicologic assessment	SNI ISO/TR 13,014:2015
	Nanotechnologies: Occupational risk management applied to engineered nanomaterials Part 2: Use of the control banding approach	SNI ISO 12,901–2:2016
	Nanotechnologies: Characterization of nanoparticles in inhalation exposure chambers for inhalation toxicity testing	SNI ISO 10,808:2015
	Nanotechnologies: Guidance on physico-chemical characterization of engineered nanoscale materials for toxicologic assessment	SNI ISO/TR 13,014:2015
	Nanotechnologies: Guidance on methods for nano- and microtribology measurements	SNI ISO/TR 11,811:2015
	Nanotechnologies: Characterization and measurement – Nanoparticles in powder form (ISO/TS 17,200:2013, IDT)	SNI ISO/TS 17,200:2015
Nanomaterial risk evaluation	Nanotechnologies: Nanomaterial risk evaluation	SNI ISO/TR 13,121:2017
	Nanotechnologies: Occupational risk management applied to engineered nanomaterials—Part 1: Principles and approaches	SNI ISO/TS 12,901–1:2016
	Nanotechnologies: Health and safety practices in occupational settings relevant to nanotechnologies	SNI ISO/TR 12,885:2016

commercialize NCC, NFC, and BNC include Nippon Paper Group Inc., Asahi Kasei Corporation, Innventia AB, Melodea Ltd., Kruger Inc., Sappi Ltd., CelluForce Inc., Daicel FineChem Ltd., American Process Inc., Fpinnovations,

Borregard ASA, J. Rettenmaire and Sohne GmbH (JRS), CelluComp Ltd., Nippon Paper Group, and Stora Enso. Those nanomaterials are mostly used for research purposes over industrial commercialization because there

have not yet been reported the application of those materials for industrial applications.

Although NLCF has not yet been applied for industrial application, Indonesian has applied other nanomaterials for industrial purposes, such as food, textile, automotive, home appliance, petroleum, cosmetic, medicine, and renewable energy; and there are 14 companies that manufacture 33 products [46]. Moreover, according to the UN Environment [50], In Indonesia LCNF has been applied by a start-up business for producing helmets in Indonesia in which the nanofibers are derived from oil palm empty fruit bunch fibers. From the above, Indonesia has the potential to develop NLCF based-industries with the GOI support, previous research, and natural fibers abundance.

5 Conclusion

NLCF isolation, characterization, and its application for industrial products have been a major research concern for bio-nanocomposite studies in Indonesia. However, the studies are still dominated with NCC and NFC over BNC and LCNF studies. Oil palm biomass is the major raw material for the obtainment of NCC, NFC, and LCNF studies due to its availability, biodegradability, and properties. *Actobacterium xylinum* is the most used bacteria for BNC synthesis carried out in static and or agitated medium. Although those materials are also provided in Kalimantan, Sulawesi, and Sumatera; Java Island still becomes the most dominated research place for NLCF. Not only the availability of raw materials but also the presence of advanced instrumentations for nanotechnology has been the reason of the phenomenon. In this study, solvent casting method is the most used and the simplest method for fabricating NLCF-based nanocomposites. The nanocomposites, which have been studied, have the potential to be implemented in varied industrial purposes, such as paper making, pharmaceutical coating agent, bioplastic, bio-foam, food packaging, table excipient, bioabsorbent, and drug delivery.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

Ethical approval All the study was carried out by systematical literature review that did not need human participants or animals performed by any of the authors.

References

1. Abrial H, Lawrensus V, Handayani D, Sugiarti E (2018) Preparation of nano sized particles from bacterial cellulose using ultrasonication and their characterization. *Carbohydr Polym* 191:161–167
2. Anwar B, Bundjali B, Arcana IM (2018) Bacterial cellulose nanocrystals from low cost resources reinforced poly(ethylene oxide) nanocomposites. *Int J Eng Res Appl* 8(1):1–5
3. Anwar B, Rosyid NH, Effendi DB, Nandiyanto ABD, Mudzakir A, Hidayat T (2018) Isolation of bacterial cellulose nanocrystalline from pineapple peel waste: optimization of acid concentration in the hydrolysis method. *AIP Conf Proc* 1708(040001):1–4
4. Arjuna A, Natsir S, Khumaerah AA, Yulianti R (2018) Modifikasi serat limbah kubis menjadi nanokristalin selulosa melalui metode hidrolisis asam. *Jurnal Farmasi Galenika* 4(2):119–125
5. Aulia F, Marpongton M, Gea S (2013) Studi penyediaan nanokristal selulosa dari tanda kosong sawit (TKS). *Jurnal Saintia Kimia* 1(2):1–5
6. Bahar N, Hidayat T, Elyani N, Rostika I (2013) The potential of nanocellulose from Acacia mangium pulp for specialty paper making. *Jurnal Selulosa* 3(1):1–8
7. Berglund L, Noel M, Aitomaki Y, Oman T, Oksman K (2016) Production potential of cellulose nanofibers from industrial residues: efficiency and nanofiber characteristics. *Ind Crops Prod* 92:84–92
8. Bufalino L, Mendes LM, Tonol GHD, Rodrigues A, Fonseca A, Cunha PI, Marconcini JM (2014) New products made with lignocellulosic nanofibers from Brazilian amazon forest. *IOP Conf Ser Mater Sci Eng* 64(012012):1–5
9. Cherlina DW, Gea S, Nainggolan H (2017) Pembuatan nanokomposit polivinil alkohol/nanoserat selulosa yang diisolasi dari tandan kosong kelapa sawit (*Elais guinensis* Jack) dengan metode ledakan uap. *Jurnal Kimia Mulawarman* 14(2):120–126
10. Chieng BW, Lee SH, Ibrahim NA, Then YY, Loo YY (2017) Isolation and characterization of cellulose nanocrystals from oil palm mesocarp fiber. *Polymers* 9(355):1–11
11. Corujo VF, Cerrutti P, Foresti ML, Vázquez A (2016) Production of bacterial nanocellulose from non-conventional fermentation media. In: Puglia D, Fortunati E, Kenny JM (eds) Multifunctional polymeric nanocomposites based on cellulosic reinforcements, pp 39–59. <https://doi.org/10.1016/b978-0-323-44248-0.00002-x>
12. da Gama FMP, Dourado F (2018) Bacterial nanocellulose: what future? *Biol Impact* 8(1):1–3
13. Espinosa E, Robles JD, Sanchez R, Tarres Q, Rodriguez A (2017) The effect of pre-treatment on the production of lignocellulosic nanofibers and their application as a reinforcing agent in paper. *Cellulose* 24:2605–2618
14. Farid M, Purniawan A, Susanti D, Priyono S, Ardhyana H (1945) Mutia E (2018) Nanocellulose based polymer composite for acoustical materials. *AIP Conf Proc* 020025:1–6
15. Global Market Insights (2018) nanocellulose market size by product (nanofibrillated cellulose, nanocrystalline cellulose, bacterial nanocellulose), by application (composites, paper processing, food and beverages, paints and coatings, oil and gas, personal care), industry analysis report, regional outlook (U.S., Canada, Germany, UK, France, Spain, Italy, China, India, Japan, Australia, Indonesia, Malaysia, Brazil, Mexico, South Africa, Saudi Arabia, UAE, Kuwait), Growth Potential, Price Trends, Competitive Market Share and Forecast, 2017–2024. <https://www.gminsights.com/industry-analysis/nanocellulose-market>. Accessed 25 March 2019
16. Harahap H, Ridha M, Halimatuddaliana TT, Iriyani I (2018) Effect of cellulose nanocrystals from corn cob with dispersion agent polyvinyl pyrrolidone in natural rubber latex film after aging treatment. *IOP Conf Ser Mater Sci Eng* 309(012101):1–5
17. Haryono A, Rohman NT (2011) Current status: development of nanotechnology in Indonesia. Expert Group Meeting “Networking of R&D Institutions in the Asia-Pacific to strengthen

- capacity of R&D Management and Innovation in the field of Nanotechnology” in 07–08 December 2011. Bangkok, Thailand
18. Iwamoto S, Yamamoto S, Lee S-H, Endo T (2014) Solid-state shear pulverization as effective treatment for dispersing lignocellulose nanofibers in polypropylene composites. *Cellulose* 21(3):1573–1580
  19. ISO (International Organization for Standardization) (2017) Summary of international activities on cellulose nanomaterials. ISO/TC 6/TG 1 (Cellulose Nanomaterials), International Organization for Standardization, Canada
  20. Jonoobi M, Oladi R, Davoudpour R, Oksman K, Dufresne A, Hamzeh Y, Davoodi R (2015) Different preparation methods and properties of nanostructured cellulose from various natural resources and residues: a review. *Cellulose* 22:935–969
  21. Jozala AF, de Lencastre-Novaes LC, Lopes AM, de Carvalho S-E, Mazzola PG, Pessoa A Jr, Grotto D, Gerenutti M, Chaud MV (2016) Bacterial nanocellulose production and application: a 10-year overview. *Appl Microbiol Biotechnol* 100(5):2063–2072
  22. Julianto H, Farid M, Rasyida A (2017) Ekstraksi nanoselulosa dengan metode hidrolisis asam sebagai penguat komposit absorpsi suara. *Jurnal Teknik ITS* 6(2):242–245
  23. Khalil HP, Davoudpour Y, Islam MN, Musthapa A, Sudesh K, Dungani R, Jawaid M (2014) Production and modification of nanofibrillated cellulose using various mechanical processes: a review. *Carbohydr Polym* 99:649–665
  24. Kojima Y, Isa A, Kobori H, Suzuki S, Ito H, Makise R, Okamoto M (2014) Evaluation of binding effects in wood flour board containing ligno-cellulose nanofibers. *Materials* 7:6853–6864
  25. Lagashetty A, Venkataraman A (2005) Polymer nanocomposites. *Resonance* 10:49–60
  26. Li B, Xu W, Kronlund D, Mänttinen A, Liu J, Smått J-H, Peltonen J, Willför S, Mua X, Xu C (2015) Cellulose nanocrystals prepared via formic acid hydrolysis followed by TEMPO-mediated oxidation. *Carbohydr Polym* 133:605–612
  27. Lu F-F, Yu H-Y, Zhou Y, Yao J-M (2016) Spherical and rod-like dialdehyde cellulose nanocrystals by sodium periodate oxidation: optimization with double response surface model and templates for silver nanoparticles. *Express Polym Lett* 10(12):965–976
  28. Martins MA, Teixeira EM, Corrêa AC, Ferreira M, Mattoso LHC (2011) Extraction and characterization of cellulose whiskers from commercial cotton fibers. *J Mater Sci* 46(24):7858–7864
  29. Maryam M, Rahmad D, Yunizurwan Y, Kasim A, Novelina N, Emriadi E (2016) Provision of micro-nano bacterial cellulose as bio-plastic filler by sonication method. *IOP Conf Ser Mater Sci Eng* 223(012040):1–8
  30. Menristekdikti (Ministry of Research, Technology, and Higher Education) (2017) Rencana Induk Riset Nasional Tahun 2017–2045. Ministry of Research, Technology, and Higher Education, Republic of Indonesia, Jakarta
  31. Missoum K, Belgacem M, Bras J (2013) Nanofibrillated cellulose surface modification: a review. *Materials* 6(5):1745–1766
  32. Mulyadi D (2010) Program Kerja BPPI Tahun 2010 dan Rencana Kerja 2011. Ministry of Industry of Republic of Indonesia, Agency for Industrial Research and Development
  33. Nikmatin S, Maddu A, Purwanto S, Mandang T, Purwanto A (2011) Analisa struktur mikro pemanfaatan limbah kulit rotan menjadi nanopartikel selulosa sebagai pengganti serat sintetis. *Jurnal Biofisika* 7(1):41–49
  34. Niyomi K, Abe M, Tsukegi T, Kuroda K, Tsuge Y, Ogino C, Taki K, Taima T, Saito J, Kimizu M, Uzawa K, Takahashi K (2018) Lignocellulose nanofibers prepared by ionic liquid pretreatment and subsequent mechanical nanofibrillation of bagasse powder: application to esterified bagasse/polypropylene composites. *Carbohydr Polym* 182:8–14
  35. Oksman K, Aitomäki Y, Mathew AP, Siqueira G, Zhou Q, Butylina S, Tanpichai S, Zhou X, Hooshmand S (2016) Review of the recent developments in cellulose nanocomposite processing. *Compos Part A Appl Sci Manuf* 83:2–18
  36. Phanthong P, Reubroycharoen P, Hao X, Xu G, Abudula A, Guan G (2018) Nanocellulose: extraction and application. *Carbon Resour Convers* 1(1):32–43
  37. Putri E, Gea S (2018) Isolasi dan karakterisasi nanokristal selulosa dari tandan sawit (*Elaeis guineensis* Jack). *Elkawnie J Islam Sci Technol* 4(1):13–22
  38. Rahayu DE, Nasarani D, Hadi W, Wrijodirjo B (2018) Potential of biomass residues from oil palm agroindustry in Indonesia. *MATEC Web Conf* 197(13008):1–3
  39. Ribeiro RSA, Pohlmann BC, Calado V, Bojorge N, Pereira N (2019) Production of nanocellulose by enzymatic hydrolysis: trends and challenges. *Eng Life Sci*. <https://doi.org/10.1002/elsc.201800158>
  40. Sacui IA, Nieuwendaal RC, Burnett DJ, Stranick SJ, Jorfi M, Weder C, Foster EJ, Olsson RT, Gilman JW (2014) Comparison of the properties of cellulose nanocrystals and cellulose nanofibrils isolated from bacteria, tunicate, and wood processed using acid, enzymatic, mechanical, and oxidative methods. *ACS Appl Mater Interfaces* 6(9):6127–6138
  41. Sánchez R, Espinosa E, Robles J-D, Loaiza J-M, Rodríguez A (2016) Isolation and characterization of lignocellulose nanofibers from different wheat straw pulps. *Int J Biol Macromol* 92:1025–1033
  42. Sijabat E, Avelina YN, Permatasari A (2017) Studi awal penggunaan nanoselulosa sebagai bahan baku pembuatan kertas. *Majalah Teknol Agro Ind* 9(12):21–29
  43. Silviana S (1855) Hadiyanto S (2017) Preparation of sago starch-based biocomposite reinforced microfibrillated cellulose of bamboo assisted by mechanical treatment. *AIP Conf Proc* 030024:1–7
  44. Solikhin A, Hadi YS, Yusram MS, Nikmatin S, Shigehiko S, Kojima Y, Kobori H (2018) Properties of poly(vinyl alcohol)/chitosan nanocomposite films reinforced with oil palm empty fruit bunch amorphous lignocellulose nanofibers. *J Polym Environ* 26(8):3316–3333
  45. Stanisławska A (2016) Bacterial nanocellulose as a microbiological derived nanomaterial. *Adv Mater Sci* 16(4):45–57. <https://www.degruyter.com/downloadpdf/j/adms.2016.16.issue-4/adms-2016-0022/adms-2016-0022.pdf>
  46. StatNano (2017) Indonesia. <https://statnano.com/country/indonesia>. Accessed 25 March 2019
  47. Subyakto S, Hermiati E, Yanto DHY, Fitria F, Budiman I, Ismadi I, Masruchin N, Subiyanto B (2009) Process development to produce cellulose nanofibers from sisal (*Agave sisalana*) and betung bamboo (*Dendrocalamus asper*). *Ber Selulosa* 44(2):57–65
  48. Sulaiman S, Mokhtar MN, Naim MN, Baharuddin AZ, Sulaiman A (2015) A review: potential usage of cellulose nanofibers (CNF) for enzyme immobilization via covalent interactions. *Appl Biochem Biotechnol* 175(4):1817–1842
  49. Tan XY, Hamid SBA, Lai CW (2015) Preparation of high crystallinity cellulose nanocrystals (CNCs) by ionic liquid solvolysis. *Biomass Bioenergy* 2015:584–591
  50. UN Environment (2017) Twelve Asian entrepreneurs awarded for forward-thinking environmental solutions. <https://www.unenvironment.org/pt-br/node/21360>. Accessed 25 March 2019

51. Voisin H, Bergstrom L, Liu P, Mathew AP (2017) Nanocellulose-based materials for water purification. *Nanomaterials* 7(57):1–18
52. Wicaksono R, Syamsu K, Yuliasih I, Nasir M (2013) Cellulose nanofibers from cassava bagasse: Characterization and application on tapioca-film. *Chem Mater Res* 13(3):79–87
53. Wijaya CJ, Saputra SN, Soetaredjo FE, Putro JN, Lin CX, Kurniawan A, Ju Y-H, Ismadji S (2017) Cellulose nanocrystals from passion fruit peels waste as antibiotic drug carrier. *Carbohydr Polym* 175:370–376
54. Xu X, Liu F, Jiang L, Zhu JY, Haagenson D, Wiesenborn DP (2013) Cellulose nanocrystals vs. cellulose nanofibrils: a comparative study on their microstructures and effects as polymer reinforcing agents. *ACS Appl Mater Interfaces* 5(8):2999–3009.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.