Guidelines for the Utilization and Application of Cellulose Nanofiber Towards the Decarbonization and Achievement of a Circular Economy

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Since FY 2015, the Ministry of the Environment has been dealing with various challenges concerning “cellulose nanofiber” (CNF), which can be expected to make a huge contribution towards the decarbonization and achievement of a circular economy, with universities, manufacturers and local governments for the purpose of facilitating its practical use in society. Based on the achievements of relevant efforts, the Guidelines containing comprehensive as well as practical information have now been compiled so that users can select a suitable type of CNF for an intended purpose in an appropriate manner and can efficiently develop and manufacture products using CNF.

Cellsulose nanofiber (CNF): Plant-derived next-generation materials

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1. Outline of Cellulose Nanofiber (CNF)

- **Characteristics of CNF**
  - Plant-derived next generation material
  - Nano-sized fiber produced through chemical and mechanical processes from wood, etc.
  - High specific surface area and has characteristics as high strength as well as modulus of elasticity despite its light weight.

- **Types of CNF**
  - Nanocrystal (CNC)
  - Nanofibers
  - Nanocellulose

2. Trends of CNF-Related Technological Development, Production and Commercialization in Japan

- **State of Dissemination of CNF**
  - Refer to “Chapter 1-1.3: Purposes of Use of CNF” and “Chapter 2-2.1: State of Dissemination of CNF and Future Marketing Prospects”

  As of 2020, several hydrophilic products using CNF have been developed and marketed. Meanwhile, many potential composite applications of CNF, such as an additive to plastics, etc., where it can offer a high level of CO2 reduction effect (automobiles, household electrical appliances, house construction materials, etc.) have reached the demonstration stage for commercial development.

- **State of Production of Raw Materials of CNF**
  - Refer to “Chapter 2-2.3: State of Production and Production System of Raw Materials of CNF”

  As of April, 2020, there is a total of 25 CNF manufacturing plants in operation and one new plant is expected to start operation in 2021. By manufacturing method, mechanical methods are most frequently used. There are three plants each for the TEMPO-oxidation method and modified pulp direct kneading process (so-called “Kyoto process”). Please refer to the Full Version for details.

3. Manufacturing Methods of CNF and Their Characteristics

- Refer to “Chapter 1-1.1: What is CNF?”

For the production of CNF, it is necessary for raw materials to undergo a refining process followed by a delignifying process using a mechanical device, etc. While CNF has multiple characteristics, the emerging characteristics differ depending on the specific raw material, pulping method and processing method. For this reason, it is important to know the type of raw material used, the processing method used for manufacture and the relationship between the functions and intended purpose of use.

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**Table 1. Characteristics of CNF**

<table>
<thead>
<tr>
<th>Characteristics of CNF</th>
<th>Expected Environmental and Other Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light weight and high strength material</td>
<td>Reduction in energy consumption and CO2 emission achieved through its application to structural materials</td>
</tr>
<tr>
<td>Plant-derived material</td>
<td>Reduction in CO2 emission as an alternative to conventional materials (plastic, etc.)</td>
</tr>
<tr>
<td>Highly recyclable material</td>
<td>Contribution to the achievement of a circular economy due to an improved level of recyclability</td>
</tr>
<tr>
<td>Procurement material from domestic forest resources</td>
<td>Contribution to forest conservation and measures designed to improve CO2 absorption sources in Japan</td>
</tr>
<tr>
<td>New material</td>
<td>Possible creation of local industries which utilize equipment, human resources, technologies, etc. associated with CNF</td>
</tr>
</tbody>
</table>

**Table 2. Classification of Nanocellulose**

<table>
<thead>
<tr>
<th>Type</th>
<th>Nanofiber (CNF)</th>
<th>Nanocrystal (CNC)</th>
<th>Bacteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>3 – 100 nm</td>
<td>100 – 50 nm</td>
<td>20 – 100 nm</td>
</tr>
<tr>
<td>Length</td>
<td>&lt; 1 µm</td>
<td>100 – 500 µm</td>
<td>1.5 – 5.0 µm</td>
</tr>
<tr>
<td>Non-crystalline</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Source: Partially added to the table from the “Report for the Feasibility Study on the Creation of Cellulose Nanofiber-Related Industries in the Chugoku Region” By the Chugoku Industrial Innovation Center (March, 2016).

**Fig 1.** CNF in wood cell wall

Source: Research Institute for Sustainable Humanosphere, Kyoto University

**Fig 2.** Transmission electron microscope photograph of CNF by manufacturing method


**Fig 3.** Examples of commodities already marketed or at the R & D stage

**Fig 4.** Panoramic view of Daio Paper Corporation’s Mihama Mill where a CNF plant is located (No.7 on the map in Fig5)

Source: Courtesy of Daio Paper Corporation

**Fig 5.** Map of CNF Manufacturing Plants (as of April, 2020)

Sources: Kansai Bureau of Economy, Trade and Industry and Kyoto Municipal Institute of Industrial Technology and Culture: “List of Companies Providing Cellulose Nanofiber-Related Samples (9th Edition)” (Feb. 27, 2020) and various public information sources

**Fig 6.** Timing of the practical application of CNF materials and market size

Source: Professor Yano, Kyoto University
3. Concrete Efforts of the MOEJ to Achieve the Practical Use of CNF in Society

Division of Work Relating to CNF among Relevant Ministries

--Refer to “Chapter 3-3.1: Entire Image of MOEJ’s Efforts to Achieve the Practical Use of CNF in Society”

Various ministries in Japan are playing their part in the utilization and application of CNF. The Ministry of the Environment, Government of Japan (MOEJ) has been conducting the evaluation and demonstration of the CO2 reduction effects of CNF and other next generation materials, contributing to the medium to long-term reduction of energy-use derived CO2 emission and also control technologies to solve problems associated with CNF recycling.

Introduction of Main MOEJ Projects Relating to CNF

Project for the Planning of Low Carbonization Measures in the Manufacturing Process of CNF Products
(FY 2015 – FY 2017)

Using the backcasting method starting from end products, various evaluation and verification exercises were conducted to identify problems at the time of manufacturing and practical use in society and prepare measures to deal with them. These exercises aimed at realizing the early practical use of CNF in society by solving possible problems in advance.

Project for Modelling Performance Evaluation of Cellulose Nanofibers
(FY 2017 – FY 2019)

In collaboration with relevant material manufacturers and product makers, possible applications for lightweight CNF materials were developed and the performance of these materials was evaluated in such fields as automobiles, household electrical appliances, housing/construction materials, etc. where there is a large potential for CO2 reduction because of the large domestic market.

Project for Demonstration of Potential Measures to Solve Problems Arising from CNF Recycling
(FY 2017 – FY 2018)

The easy recyclability at the manufacturing stage of composite CNF resins (materials) and performance of recycling materials were evaluated and solutions to perceived problems were demonstrated.

In 2016, the NCV (Nano Cellulose Vehicle) Project started as an entrusted project of the MOEJ, Kyoto University acted as the leader of the project in a consortium made up of a total of 22 universities, research institutes, private enterprises, etc. As a positive achievement of this project, a concept car manufactured with composite CNF materials was introduced at the 2019 Tokyo Motor Show for the first time.

--Refer to “Chapter 3-3.1: Entire Image of the MOEJ’s Efforts to Achieve the Practical Use of CNF in Society”

Table 3: Technological Potential for NCV (Petrol-Powered) in 2020

<table>
<thead>
<tr>
<th>Contents</th>
<th>Technological Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle weight reduction (including secondary weight reduction)</td>
<td>16%</td>
</tr>
<tr>
<td>Fuel efficiency improvement effect (including engine downsizing)</td>
<td>11%</td>
</tr>
<tr>
<td>Lifecycle CO2 emission reduction effect (efficient mass production scenario for CNF)</td>
<td>2t-CO2e/vehicle</td>
</tr>
</tbody>
</table>

Fig.7: NCV introduced for the first time in 2019

The MOEJ has clearly put forward a future image of a “decarbonized society, circular economy and decentralized society” utilizing CNF, indicating the direction for policies and measures designed to achieve these targets so that these policies, etc. will form the foundations for efforts to use CNF and to increase investment in CNF-related businesses.

Current Selling Prices of CNF

--Refer to “Chapter 3-3.2: Outline of CNF-Related Projects”

Based on data provided by the entrustee for the Project for Modelling Performance Evaluation of Cellulose Nanofibers of the MOEJ and other information, the current selling prices of CNF by manufacturing method are sorted. The cheapest price found (500 JPY – several tens of thousands JPY/kg) is for CNF produced by the mechanical processing method. In contrast, the price becomes lower as the use of such chemical treatment processes as the TEMPO processing and modified pulp direct kneading methods ranges from 3,000 JPY to several tens of thousands JPY/kg (10 – 30% CNF equivalent). Such a price difference is assumed to reflect the level of defibrilition of CNF and number of treatment processes involved in manufacturing.

The market price of CNF is determined by the type of application and quality of corresponding product. In highly value-added fields (pharmaceutical products, etc.), business transaction is feasible even if the selling price is high. For structural applications (automobiles, household electrical appliances, construction materials, etc.), a high market price cannot be expected despite a large market size, making it necessary to lower the current selling price to expand the use of CNF.

Example of Region-Based Efforts

Fuji City, Shizuoka Prefecture

In Shizuoka Prefecture and Fuji City where the paper industry is long established as a major local industry due to forests, a regional consortium has been formed under administrative leadership to provide vital information and to assist cooperation between enterprises with a view to creating new industries using CNF.

--Refer to “Chapter 3-3.3: Creation of Local Industries Using CNF”

Fig.9 Examples of merchandise developed by platform members for practical use

Fig.10. Fuji City CNF Platform

Sources: Fuji City platform website
4. Q&A Concerning the Guidelines

Question 1: Who are the targets of the Guidelines? What is the scope of the contents of the Guidelines?

The assumed readers of the Guidelines are all stakeholders involved in the manufacture of CNF, R&D of products using CNF and actual use of CNF. The scope of the Guidelines covers the entire supply chain of CNF, primarily featuring the stages from manufacture to transportation and products using CNF.

→Refer to “Introduction 3: Target Readers” and “Introduction 4: Scope of Application” of the Main Version

Fig.11 Entire image of the CNF supply chain

Question 2: How have MOEJ projects subsequently developed into efforts by enterprises?

Some enterprises have continued their own technological development efforts while others have already developed products or entered into joint research with other universities and/or research institutes.

→Refer to “Chapter 3 : Contents of CNF social implementation efforts by the MOEJ” and Separate Volume 1 : Achievement summary of MOEJ Projects Relating to CNF” of the Main Version

Question 3: What are the local advantages of the creation of local industries using CNF? What roles are the main local players expected to play for the creation of local industries?

The expected positive effects include an increase of the local GDP, lowering of the unemployment rate and increase of the average hourly wage. Trial calculations by the MOEJ have produced the following results (in the case where 43,000 tons of masterbatch containing 10% CNF are produced annually).

- Amount of newly created local demand: approximately 127 billion JPY
- Real GDP growth rate: approximately 4%
- Number of induced employment: approximately 2,500

One key point to achieve these positive effects is “to secure an enterprise(s) which locally manufactures products” in addition to the establishment of a standard supply chain. Moreover, cooperation with enterprises and knowledgeable persons inside and outside a specific locality is necessary for the creation of outlets for CNF and an increase of the demand.

Local governments are expected to play a leading role in such cooperation and their efforts together with neighboring local governments to create local industries will lead to the vitalization of the entire area.

→Refer to “Chapter 3-3: Creation of Local Industries Using CNF”

The section referred to above lists concrete numerical values, etc. for the economic and employment creation effects based on case studies using multiple patterns.

Table 4. Functions required of a local consortium

<table>
<thead>
<tr>
<th>Necessary Human Resources</th>
<th>Description of Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organizer (Local Government, etc.)</td>
<td>Lead the collaboration and active perception of many stakeholders</td>
</tr>
<tr>
<td>Coordinator</td>
<td>Accurately guide and support the project until a concrete building</td>
</tr>
<tr>
<td>Key Persons (Scientists, etc.)</td>
<td>As an expert, accurate advice for promoting initiatives if necessary; Meeting coordinator</td>
</tr>
<tr>
<td>Business Operators</td>
<td>Develop projects; Create new business</td>
</tr>
<tr>
<td>Forestry Association, etc.</td>
<td>Disclose information related to production; Transportation functions and supply and demand</td>
</tr>
<tr>
<td>Administration (Central Government)</td>
<td>Provide information on issues such as regulations and measures that can be supported by the national government</td>
</tr>
</tbody>
</table>

Table 5. Comparison of Recycling-Related Characteristics by Type of Material

<table>
<thead>
<tr>
<th>Material Recycling</th>
<th>Thermal Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNF</td>
<td>Composite</td>
</tr>
<tr>
<td>High</td>
<td>Highly feasible due to less deterioration, in turn due to fewer ruptures of the fibers during recycling</td>
</tr>
<tr>
<td>CNF (glass fiber reinforced plastic)</td>
<td>CFRP (carbon fiber reinforced plastic)</td>
</tr>
<tr>
<td>CFRP (glass fiber reinforced plastic)</td>
<td>Highly feasible due to less deterioration, in turn due to fewer ruptures of the fibers during recycling</td>
</tr>
<tr>
<td>CFRP (carbon fiber reinforced plastic)</td>
<td>Less feasible due to the problems of a low processing efficiency, etc., in turn caused by such properties as insubstantiality, fire-resistance and/or heat resistance</td>
</tr>
</tbody>
</table>

Question 4: Recyclability is mentioned as one characteristic of CNF. What advantages does composite CNF material have compared to other materials?

Compared to GFRP (glass fiber reinforced plastic) and CFRP (carbon fiber reinforced plastic), both of which have mechanical properties similar to those of composite CNF material, composite CNF material has such characteristics as less property deterioration after repetitive recycling due to few ruptures of the fibers during recycling. Moreover, thermal recovery is applicable to composite CNF material just like paper and plastic because of the combustibility of the plant-based raw materials for CNF.

→Refer to “Chapter 4: Recycling of CNF” in the Main Version

Question 5: How much can CO2 emission be reduced by the utilization of CNF? How is such reduction calculated?

By exploiting its characteristics, CNF can be expected to respond to various social conditions concerning sustainability through business activities. Effective ways for enterprises, etc. to market products responding to the social conditions include quantitative review of the advantages of utilizing CNF and communication with stakeholders based on the review results.

From such viewpoint, there has been increasing importance of LCA, especially establishing lifecycle CO2 (lLCCO2) from the procurement stage of raw materials to the disposal stage, and the effective use of the obtained data in addition to CO2 data during the period of active use.

The CO2 reduction volume can be calculated following the flow in the diagram on the right. The estimation result for petrol engine cars incorporating CNF materials shows that there is a CO2 reduction effect to the tune of 2 tons per car compared to conventional petrol engine cars. In the Main Version, similar CO2 estimation results are listed for other types of products.

→Refer to “Chapter 5: Calculation of the CO2 Reduction Effects of CNF” in the Main Version and “Separate Volume 3: Guidelines for Calculation of the GHG Reduction Effects of CNF”

Question 6: What are the assumed new fields for CNF application in the future and what are the presently assumed issues to be dealt with?

From the viewpoint of reducing the environmental load through global warming control measures, etc., the MOEJ will continue to promote the application of CNF, particularly focusing on the three fields of mobility, house construction materials and household electrical appliances. Particularly promising fields for development are “small electrical mobility products” and “batteries/condensers”.

The principal issues assumed at present are listed below.

- Improvement of performance and guarantee of quality
- Reduction of manufacturing and transportation costs
- Establishment of recycling methods, etc.

The MOEJ is hoping that the Guidelines will provide the opportunity for the utilization and application of CNF towards the achievement of a decarbonated society and a circular economy and society.

→Refer to “Chapter 6: Towards the Future Utilization and Application of CNF”