The Green Fibre Bottle Idea

The general idea of the green fibre bottle is to produce liquid packaging from 99.99% fibre materials and less than 0.01% sustainable minerals. The fibre sources can be any fibres – recycled or new fibre from any sources in the World. Energy use for separating water and fibres in a pulp is minimal by using Impulsive Drying Technology. The green fibre bottle focus to replace all liquid packaging using plastics – and can also replace all other packaging materials.

Our technology can in the end replace all kind of plastic packaging.

The green fibre bottles can after use be re-use, recycled, incinerated with energy production, biodegraded or composted. The project has the main focus to recycle as this solution in the end is the best circular design option.

Our project has the support of Carlsberg Breweries.
Circular Economy of the Green Fibre Bottle

The linear fibre flow is traditional as follows:

Forest → Wood → Pulp → Fibre-based packaging material → Converting to packaging → Packing/Filling → Distribution of packed products → Packaging waste → Waste management

From World Economic Forum report: Towards the circular economy, following model illustrate the situation about forest-based wood fibres today.

Green Fibre Bottle will accelerate the scale-up across global supply chains of liquid packaging as follows:

The fibre bottle can be produced from both virgin and recycled fibres. After the bottle is used the used bottles can be compacted and efficient transported back to pulping for new fibre bottles.
In order to optimise food safety virgin and recycled fibres can be separated under the bottle moulding process. The virgin fibres will be placed on the inside to minimise the safety challenge. Recycled fibres on the outside. If recycling rates improves the virgin layer can be minimised and exchanged with recycled fibres. If utopic conditions are reached sometime in the future and the fibre bottles are only produced of recycled fibres the inner coating can be improved to the new condition. Recycled fibres can even be build up in several layers of different recycled origin.

**Sourcing raw materials**
The new moulding process use three different sources that each also can be included applied in several layers in the final materials and products. These three different sources are:

**Fibre sources (98-99%)**
Any kind of fibre sources can be used. It is important to select inexpensive fibres from waste materials that is not used for food or other more important purposes. The sources can be:

**Recycled fibres**
- Used newspapers are the most inexpensive source but contain also oil-based printing inks that is not able to have food contact.
- Used fibres from packaging, books etc. have not the oil-based printing inks but do still contain un-known substances with challenges for food contact.
- Etc.
**Virgin fibres**
- Virgin paper fibres produced for food contact
- Fibres from plants that is not used for other purposes as:
  - Banana leaves
  - Coconut fibres
  - Brans
  - Seaweed
  - Etc.

**Bio-coatings (1-2%)**
The coatings needed as intermediate coating layer shall be made out of a bio-origin as:
- Starch
- PLA
- Cassin
- Fish scales
- Etc.

These bio-coatings can have an acceptable oxygen barrier but are not working as a water and humidity barrier. As most food contain large amounts of water something more is needed.

**Nano-coatings (<0.01%)**
As bio-materials performs poor to water and as a humidity barrier an ultra-thin layer of a mineral is needed on the surfaces. The coatings can be made of:
- SiOx
- DLC (Diamond Like Carbon)
- Grafting
- Etc.

**Structure in circular flow of fibre bottles**

![Diagram showing the circular flow of fibre bottles](image)
Bottles and other products can be made out of any kind of fibres including recycled fibres. The bottle at the right is only made from used newspapers. For products with contact to food must apply all regulations for food contact materials. Basically the plasma coating is the only material with direct food contact. But as the plasma coating is ultra-thin cracks can occur and the fibre material can be designed in several layers with the first layer as a thin virgin fibre layer.

In bottle and other product recycling no separation will be needed. The used fibre materials only have to be cleaned before these are re-pulped to new bottles. The two coating layers are not separated from the bottles. The small amount of bio-coating will be soluted in the pulp and mostly separated in the pulp water. The marginal amount of minerals used for the plasma coating will end as a filler in the next bottles/products. This is not a problem as paper anyway use different kind of mineral fillers as calcium, TiO$_2$ etc.

The first production tests of bottles indicate both positive and negative effects of using recycled fibres. The recycled fibres form better and create more details in the mould, but the recycled fibres do not have the same strength.

In the end more than 99,99% will be bio-fibres – both fibres (98-99%) and the intermediate coating (1-2%) will be bio-based and basically made from fibres. Less than 0,01% will be sustainable minerals as SiOx, DLC etc.

**Circular economy and green fibre bottles**

*Sustainability and packaging economy is closed related to the weight of the selected packaging.*

The fibre bottle has less than half the weight than a PE plastic bottle.
The lighter recycled bottle has a compression strength 17% better than the plastic bottle and the 100% virgin fibre bottle performs 100% better than the PE plastic bottle.

Most likely the fibre bottles can be weight reduced more in order to upgrade both economy and sustainability.

The economy in the fibre bottles are also excellent

Variable costs for 330 ml. bottles:

- PE plastic: 0.038 €/bottle
- PET plastic: 0.018 €/bottle
- Virgin fibres: 0.009 €/bottle
- Recycled fibres: 0.006 €/bottle

New equipment a business challenge

The price difference between plastic bottles and fibre bottles measured in only variable costs absolutely in favour of the fibre bottle that only cost 17-25% of the most inexpensive plastic bottle. In first view the business case looks perfect but in reality the bottle producer must invest a large value in new equipment. Machines for the existing packaging materials are already invested, payed and work every day. Both investments are really large and will be a significant bottleneck for the introduction of new and more sustainable packaging technology. The unbalance between the relative large investments in production equipment and marginal variable costs have always been an extreme conservative factor in the packaging business.

EcoXpac has made a first estimate of the investments for a new bottle production line.
### The Market for the Green Fibre Bottle

The total market for packaging for liquids is very large and accounts for 30-35% of the total packaging market.

The market for packaging for liquids is:

- **Denmark:** about 0.5 billion € = 5-7 billion bottles
- **EU:** about 27 billion € = 300-400 billion bottles
- **World:** about 80 billion € = 900-1200 billion bottles

Just a marginal fraction of this large market will be an explosive development of EcoXpac.

### Market Introduction and Partnerships

Packers and fillers will in most cases purchase the empty packaging as bottles from producers nearby. Empty bottles are expensive to transport over long and medio-range distance as it is expensive to transport air.

The fibre bottles from EcoXpac has following solutions to these challenges:

- The fibre bottles from EcoXpac can be filled on the existing filling equipment with none or only minor upgrades.
- The compact equipment from EcoXpac is designed to be installed in the beginning of a standard filling line. Compacted recycled or virgin fibres are 98-99% of the raw materials.
EcoXpac has following strategies to introduce these investments in fibre bottles:

1. EcoXpac will have a pilot production plant for fibre bottles. This pilot production plant can deliver smaller quantities of fibre bottles for the first production and market tests.

2. EcoXpac can later deliver and install the compact equipment on the packer and fillers sites.

3. EcoXpac can deliver and install the compact equipment to local packaging producers.

4. EcoXpac can install and run own compact equipment at the packer and fillers sites.

Maturity of the Green Fibre Bottle and next steps in the development

State of the art
The projects concerning the development of functional fibre bottles include several national and private projects whose overall beginning dates back to 2009. These projects can be categorised into two main areas of activity:

1. Pilot production of fibre bottles that have the same shape and characteristics as plastic or glass bottles. EcoXpac has already developed very promising fibre bottles in a high quality that in most cases perform better than bottles in glass and plastic. EcoXpac already now has an operational small-scale prototype/pilot production of fibre bottles that can be used for a wide range of products.

2. Coating of these fibre-based bottles has up until now been undertaken at Danish technological Institute (DTI), whose laboratory PECVD setup allows for a versatile plasma coating development process. DTI’s setup allows for most types of chemistries to be experimented with, but so far, development has been focused on silicon-based coatings. Research on carbon-based coatings has been initiated. Fibre bottles have been successfully coated in DTI’s laboratory with a silicon-based coating to such a level that the barrier specifications are today at par with plastic bottles.

There are examples in the literature and from the industry of development and implementation of a carbon-based coating called diamond-like carbon (DLC), which is a good candidate for coating implementation in an industrial scale production, as it only requires a low vacuum. Furthermore, DLC can be manufactured from different carbon-based precursors, which have the manufacturing advantage of low molecular weight.

Currently, partially sustainable competing products do exist. One such product is the PaperBoy bottle, featuring a moulded cellulose outer shell to provide rigidity with a plastic bag container and a plastic/metal closing mechanism. However, the advantages of the proposed solution include: full biodegradability, easier waste management, sustainable sourcing; which all support consumer preference. Nevertheless, both products will likely have a market share.
EcoXpac is working on an ongoing project financed by Innovation Fund Denmark that has the scope of producing a small-scale fibre-based bottle production line. The production line is expected to be operational in 2020. These bottles lack any kind of coating in the final stage of this production and can therefore not be used for food (dry or liquid). For this reason, there is a technological gap until the launch of fibre bottles on the market.

![The first moulding machine from 2015 with wet forming mesh on the right and the impulse drying mould on the left.](image)

### Coating of fibre bottles

In 2015 DTI finalised the project: \( SiO_xC_yH_z \) coatings on packaging. The results from the project indicate that two complementary layers of coating are needed to meet the necessary water, moisture and gas barrier properties.

| 0.01% SiO_xC_yH_z | 1-2% bio-coating | 98-99% fibre material |

**Internal coating structure**

The first deposited coating layer is a biodegradable material that smoothenes the rough surface of the fibre-based material used to produce the bottles. The fibres form a chaotic three-
dimensional mesh with comparably large pores on which it is impossible to deposit a functional gas barrier using a nanometre-scale film. The layer of biodegradable coating has a thickness of 20-100 µm and gives the paper surface an oxygen barrier. The range of materials that can be used for the intermediate layer can come from different grades of sustainability, but also properties. These materials have a relatively acceptable oxygen resistance but both water contact and moisture resistance is poor. The choice of the final material will happen during the course of the project.

Two coating layers on a paper substrate – 10-100 µm bio intermediate barrier layer on left with 20-100 nanometer SiO$_x$C$_y$H$_z$ top layer

Different compositions of SiO$_x$C$_y$H$_z$ give different performance to oxygen and vapour transmission over the bottle barrier
The research so far has documented a trade-off between oxygen and vapour barrier performance. These coatings are fine for many products as sauces, ketchup, milk, tablets, sodas etc. But the coatings do not have an acceptable performance with regards to other products such as beer, instant coffee, baby food, wine etc. More research will be needed to reach all demands.

After the deposition of the preliminary coating, a nanometre-scale coating layer of a silicon-based polymer (with the general formula SiO\textsubscript{x}C\textsubscript{y}H\textsubscript{z}) is deposited using plasma enhanced chemical vapour deposition (PECVD) process. The experimental results show barrier properties much better than bottles made in PE and PP.

Late in 2016 new results showed oxygen and water vapour barrier properties better than those of metallised plastic films. It is therefore expected that the production of fibre-based bottles that are superior to PET bottles is possible. However, these results have only been achieved in a laboratory environment so far.

The challenge with the deposition of such thin plasma coatings is its sensitivity towards surface roughness. This constitutes a major technical barrier as the surface inside a fibre bottle tends to be fairly rough. To overcome this, a number of technical efforts are being developed such as:

- Optimizing the internal fibre surface by tailoring the fibre stock recipe
- Optimizing the bottle forming and drying procedure
- Applying a smoothening first coating layer

**Production speed**

High production speed is necessary in order to achieve a good economy in the process and the packaging solution. This is the case for all unit operations in the bottle production (forming, drying, barrier coating etc.). The need for smooth surfaces affects the production speed as strategies to create smoother fibres surfaces often affect dewatering rates. Also, if the smoothening first coating layer is applied as a water-dispersion, then there is a challenge to subsequently dry the bottle. Besides this, there are several aspects connected to the SiO\textsubscript{x} treatment as will be described below:

Working with different compositions of SiO\textsubscript{x}C\textsubscript{y}H\textsubscript{z} has posed its own challenges: [This section, the two numbered lists are a bit hard to follow. Can you give some additional text explaining this?]

1. Too high vacuum is needed (0.2-0.5 mbar), which has the following consequences:
   - A relatively long processing time, also leading to:
     - Extra dewatering of the cellulose and starch-based coatings
     - Crystallization and cracking of starch-based coating during PECVD
   - More expensive equipment
   - Difficulty to hit a proper stoichiometry (x-index value) to reach the target barrier
2. The precursor in the plasma has a high molecular weight (heavy) and toxic and is non-renewable
3. Large amounts of CO\textsubscript{2} are emitted as a by-product of the PECVD process at industrial throughput level of thousands of bottles per hour
For these reasons, and to reach a high production speed, the project needs to look for another plasma top coating.

Diamond-Like Carbon (DLC)

A promising candidate for replacing SiOₓCᵧHₓ is Diamond-Like Carbon (DLC). This coating has the following promising characteristics:

1. Low vacuum is needed 200-500 mbar (50-80% vacuum) and has the following positive attributes:
   - Shorter processing time, leading to:
     - Minimal deteriorations of starch coating

2. Cheaper equipment
   - Cheaper equipment
   - Minimal deteriorations of starch coating
   - Relatively easy to hit between sp² and sp³ hybridizations to reach the target barrier

3. 2. Light and relatively renewable precursor (ethylene, C₂H₄). It can be accumulated as a product of fresh-produce respiration process that will improve sustainability.

4. No CO₂ emission

5. Potential improvement of oxygen barrier of polymers by a factor of about 50.

The aim in this project is to surpass the current state-of-art by developing a coating system capable of reaching a production speed of 1,500 bottles per hour with the potential to increase to a higher production speed within two years. It is also aimed to achieve a barrier coating able to provide protection to all types of food and beverages.

Ongoing activities

EcoXpac is involved in cooperation with Carlsberg and the DTI in a national project entitled “Impulse drying of cardboard moulded 3D structures” (2015-2020) financed by Innovation Fund Denmark under the Danish Ministry of Higher Education and Science. The aim of this project is to develop and produce a fibre bottle-making machine with the capacity of 1,500 bottles per hour. This project only focuses on bottle manufacturing and has no activities regarding coating deposition. The machine is under construction at the moment. Preliminary results from the development of both paper pulp and drying technology have already demonstrated fibre bottles of an extremely high quality with a very smooth surface. With the current proposal our consortium hopes to reduce the thickness of the intermediate bio-coating to a minimum using these new technologies.
Beyond the state-of-the-art

The ambition in this project is to develop, build and test a coating production line with a capacity to produce 1,500 fibre bottles per hour. This will be the production speed for small filling lines. However, it should be possible with additional resources and refinements in a post-project phase, to reach a minimum of 20,000 fibre bottles per hour, which is the production speed required for large-scale production facilities (i.e., 5-6 bottles per second).

The project will combine the previous expertise of the partners and knowledge from the literature into a system that will supply fibre-based bottles with all necessary barriers, both internal and external. The key to a sustainable biodegradable coating solution is the combination of several experimental and tested technologies, which will be provided by the project: bio-based biodegradable smoothening barrier coatings, biodegradable silicon- or carbon-based PECVD barrier coatings, bio-based surface-modifying grafting process. Initial implementation of these technologies in a laboratory environment will lead to an upscaling to the goal of 1,500 bottles per hour.

Specific challenges

a) Challenges due to recycling of fibres

In order to develop sustainable fibre bottles this project must solve the following challenges from the recycling of the fibres:

- In order to meet the requirements of a circular economy, the fibres used for pulping and converted into bottles need to have a specified quality. Thus, the used bottles must be recyclable into new fibre bottles or other products. Under recycling the fibre lengths tend to get shorter and shorter providing better quality bottles. However, in the process of recycling the coating substances accumulate in the paper material presenting a major challenge. This project will investigate appropriate control measures to counter this process.

- Cellulosic food contact materials containing recycled fibres can be a challenge due to the sometimes uncertain composition of the material. Legislations and recommendations exist for food contact materials; the prime principle is written in Regulation (EC) No 1935/2004 and states that materials and articles must not transfer their constituents to food in quantities which could (a) endanger human health, (b) bring about an unacceptable change in the composition of the food, or (c) bring about a deterioration in the organoleptic characteristics. Composition and purity criteria that must be met by these materials are described in additional legislations and recommendations. In light of these regulations, the project must design a strategy for this challenge by ensuring that the barrier coating on the inside of the bottles is functional and prevents migration of contaminants to the food, and therefore that the bottles present no risk for the consumer.

b) Challenges with plasma coating in vacuum

A proof-of-concept experiment has been carried out at DTI where the plasma coating deposition is done in high vacuum (1-10 Pa). This low pressure demands special pumps and time to create the optimal conditions.
bottles per hour (25 units per minute) alternatives will be needed. Solving this problem can be done by using the following strategies:

1. Upgrade pump capacity
2. Work with large batches, and/or
3. Change the coating system to another coating only needing normal industrial vacuum (0.1-0.5 bar).

c) Challenges for usability

Fibre bottles are different from other liquid packaging. For this reason, the fibre bottles will react differently in their use during their life cycle, namely the filling process, distribution, sale and consumers’ use.

Award category

EcoXpac apply for an Advanced Accelerator Ready Idea Prize of $200,000.

EcoXpac

EcoXpac is a small development company with the mission to develop the green fibre bottle to the world market. The company has about 30 employees in Slangerup 40 km. North of Copenhagen, Denmark. EcoXpac A/S is owned by different shareholders with the dominant owner, Jesper Servé owning more than 50% of the company. The large paper producer, BillerudKorsnäs own 10% of the shares in EcoXpac.

EcoXpac has participated in following projects:

- Green fibre bottles, 2011-2013, Danish Business Authority
- Production of Green fibre bottles from recycled paper, 2013-2016, Danish Business Authority
- SiOxCyHz coatings on packaging, 2013-2015, Innovation Fund Denmark, Ministry of Higher Education and Science
- Impulse drying of cardboard moulded 3D structures, 2015-2020, Innovation Fund Denmark, Ministry of Higher Education and Science

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Prototyping and Pilot Production

EcoXpac is already now able to produce small numbers of fibre bottles on the existing pilot production facilities. Prototypes can be shipped for the evaluation.

The coating equipment is still on laboratory level. DTI is able to produce a few prototypes for demonstration. These prototypes demonstrate excellent performance better than metallised films.

Use of the Award Prize and other sources

As the coating technology is the biggest gap between small production of fibre bottles the resources from the $200,000 from the Advanced Accelerator Ready Idea Prize will be invested in a pilot production coating line for fibre bottles. The investment is estimated to about us$ 1 million and EcoXpac must find other supporters or investors to overcome this important challenge to proceed with the project.