Safe and Sustainable by Design development of nanomaterials for green printed electronics.

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Sustain-a-Print (SaP)[1] project embraces the EU's Circular Economy Action Plan[2] to further advance the circularity potential of electronics and electronic equipment by the dire forecast for increased resource extraction and waste generation and their detrimental effects on climate and biodiversity (Figure 1).

Printed electronics (PE) is an additive manufacturing method characterized by its versatility, scalability, and low material usage[1], by printing conductive and dielectric inks on flexible/stretchable substrates opening new applications in the market. However, in traditional electronic production methods, the current life cycle for a PE product starts with materials (substrate, conductive and dielectric materials) obtained through mining of raw materials. The main goal of Sustain-a-Print (SaP) is to open new life-cycle routes and to design and implement sustainability into each step of the lifecycle (Figure 2).

The main objectives of the project are:

1. The **reuse and recycling** of valuable PE materials, thus contributing to a circular economy in the EU using **Safe and Sustainable by Design (SSbD)** methodologies.
2. Development of **sustainable materials and formulations** for PE, utilising either bio-based or recycled electronic waste sources, using **SSbD methodologies**.
3. Development of **sustainable formulations** for PE printing, using **SSbD methodologies**.
4. Development of **sustainable digital printing and assembly** of PE to address IEU specifications based on sustainable materials and formulations, using **SSbD methodologies.**

Nanomaterials have a crucial impact on printed electronics, providing multiple benefits and driving innovation in the development of **electronic devices**. Nanomaterials are pertinent in this context because of their distinctive characteristics, which augment the **efficacy and adaptability** of printed electronic devices[3].

The main ways of impact of nanomaterials on printed electronics are: (1) in their use as **conductive** nanoparticles, with nanomaterials like silver, gold, copper, and graphene, (2) **their flexibility and stretchability** with nanomaterials like Carbon Nanotubes, crucial on applications like wearable electronics and flexible displays, (3) their **enhanced performance**, offering superior electrical, thermal and mechanical properties compared to their bulk counterparts, (4) its s**mall size and high aspect ratio**, which enables their miniaturisation and possibility to create smaller and more compact devices, (5) nanomaterials can be **cost-effective** and allow the reduction of material usage while maintaining high performance, (6) their **compatibility with various printing techniques**, such as inkjet printing, screen printing and roll-to-roll printing[4].

The **potentially harmful effects of nanoparticles** on **human health and the environment** are a matter of great concern and are being extensively studied. Nanomaterials possess distinct physical and chemical characteristics due to their diminutive size and extensive surface area, potentially resulting in diverse **toxicological consequences** when compared to their larger counterparts.

Toxicity and ecotoxicity of nanomaterials depend on their Size, Surface Chemistry, Biological Interactions, and Bioavailability among others. Thus, standardized methods for risk assessment need to be developed, for toxicity studies, but also, for risk assessment and for establishing safe exposure limits[5].

The **Safe and Sustainable by Design strategy** adopted by the project will allow us to mitigate risks and potential hazards in the products developed within the project. These strategies will be based on the properties of the materials and processes under study in the project to reduce their impact on health and the environment. The strategies will be divided into **Safe by Product Design**, which will be focused on the mitigation of the potential hazards of new nanotechnology products to improve biocompatibility and **Safe by Process Design**, based on containment approaches and engineering techniques to remove ultrafine particles released at relevant stages in the life cycle, from the synthesis to the EoL[6].

These approaches and methodologies will be demonstrated through the development of a green and safe electrochemical enzymatic lactate sensor. Analytical figures including sensitivity, repeatability, limit of detection and robustness will be compared with artificial and real samples. The consortium of the project will also develop and validate an electronic Membrane Switch made of sustainable materials, conductive and dielectric inks and substrates for the production of digitally printed prototypes.

References

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Figures

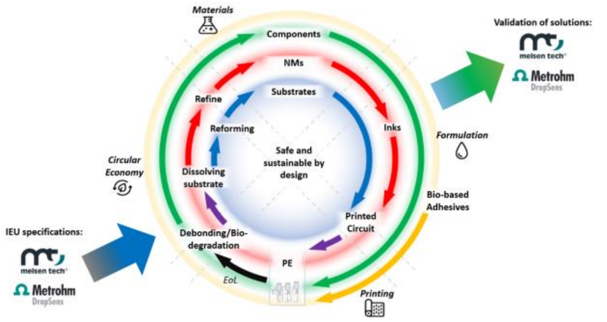

Figure 1: The SaP concept for sustainable PE production based on recycling/biodegradation of NMs and substrates, and reusability of components. IEU specifications will be addressed by applying the SaP concept as a foundation for the SaP methodology guided by SSbD activities.[1]

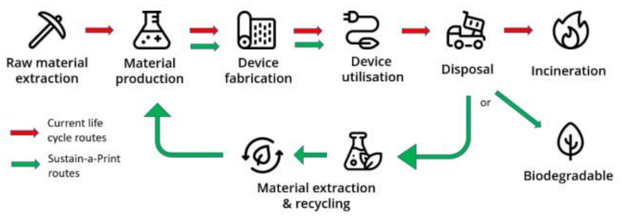

Figure 2: Illustration of current life-cycle routes for PE based on processes and the sustainable alternatives that are considered in SaP.[1]