Can a tiny sensor material have a big sustainability impact?

Sensors help factories detect problems earlier and use resources more efficiently. However, the thin materials that enable these functions may be connected to complex supply chains and uncertain recycling routes. This thesis examines indium-based sensor materials and shows why even tiny functional layers deserve sustainability attention.

Sensors are becoming more and more important in modern manufacturing. They can be integrated into tools, machines or engineering parts to monitor information such as temperature, vibration, wear and processing stability. This information can help factories detect problems earlier, reduce defective products, avoid unnecessary downtime, and use materials and energy more effectively.

However, sensors also rely on specific materials to achieve functions. This thesis focuses on two indium-containing materials: indium oxide and indium tin oxide, that is, ITO. They can be made into very thin films and used as functional layers in sensor systems. Although the amount used in each product may be small, there is still a greater sustainability problem behind these materials.

The key issue is indium. Indium is usually not specially mined as the main metal but mainly recovered as a by-product from zinc production. Therefore, the supply of indium depends on zinc ore production, refining capacity, recovery technology and economic conditions. The supply of indium is also geographically concentrated, which may make downstream users more vulnerable to trade changes, policy adjustments, or regional supply interruptions.

The downstream stage is equally important. When indium oxide or ITO is integrated into engineering products, it becomes part of a multi-material system and may be combined with substrates, coatings, wires, protective layers and electronic components. During the use stage, this integration can support monitoring and maintenance. However, after the product reaches end of life, this thin layer of sensing material may be difficult to identify, separate and recycle.

It is relatively more realistic to recover indium from manufacturing waste, such as used ITO sputtering targets, because such materials are more concentrated and easier to collect. However, the scrapped sensor products are different. The indium-containing layer is usually very thin, dispersed, and firmly attached to other materials, so the recycling path is more uncertain.

Health and handling problems also need to be paid attention to. The protected sensing film in the finished product is not equivalent to indium dust. Higher risks usually occur during manufacturing, cutting, disassembly or recycling, because these stages may produce inhalable indium-containing dust. Long-term exposure to such dust can cause serious lung health problems, so safe operation and material tracking are very important.

This thesis does not simply judge whether indium-containing sensing materials are "good" or "bad". On the contrary, it shows that such materials need to be understood by weighing the relationship: on the one hand, the challenges of supply, processing, recycling and safe handling should be considered; on the other hand, it should also be seen whether the sensor can reduce waste, rework, downtime, tool failure or energy consumption during the use stage.

The main message of this thesis is that a very small sensing material layer should not be ignored. Even if the amount is small, advanced functional materials may be connected to complex supply chains and uncertain recycling paths. Future research needs more specific application data to judge under what circumstances such materials are justified.

Mini Dictionary:

- **Indium** is a metal often recovered as a by-product from zinc production and used in materials such as ITO.
- **ITO** means indium tin oxide, a material used in thin films, displays, coatings, and sensor applications.
- **Life-cycle perspective** means looking at a material from sourcing and production to use, recycling, and disposal.
- **Break-even calculation** means estimating how much benefit is needed to compensate for an added burden.