I The SUSNANOFAB Action Plan

The SUSNANOFAB Action Plan is a key component of SUSNANOFAB Roadmap, aimed at identifying key research and innovation actions where public and private stakeholders may invest in the near future for unleashing the full potential of nanofabrication. The objectives of the action plan activity are:

- to collaboratively consolidate the work carried out in the development of the reported actions and to further refine its contents;
- to leverage a larger number of experts, in order to enlarge the perspective of the action plan, to add more actions, either cross-cutting or sectorial, considering key sectors not duly represented at the moment (i.e., energy & smart mobility, construction, etc.);
- to determine the priority/timeline of the action and the international relevance: a rating is reported from previous meeting, where approximately 30 experts attended.

SUSNANOFAB action plan has been derived from a re-clustering process of SUSNANOFAB experts' inputs provided for the challenges identified throughout SUSNANOFAB former meetings. In this process, twelve recurring clusters of concepts were identified:

1. Reduction of production costs, cost-efficient processes.
2. Scaling up of the new nanotechnology-enabled manufacturing processes both for nanomaterial and nano-enabled material production.
3. Lack of efficient mass-production techniques, methods, and manufacturing capacities causes inconsistent properties in scale-up and impairs process cost-efficiency. Unreliable results are a barrier for adoption in several sectors, including the automotive industry.
4. Metrology for quality control; Production of 3D structures.
5. Lack of investments in nanotechnology, especially for energy production.
6. NEMS and MEMS meeting the requirements for mobility sector, nano-sensors for water, soil, and air monitoring; sustainable power sources for wearable devices; Energy efficiency of nanoelectronics
7. Smart delivery systems require full regulatory approval; extensive clinical safety testing is required for nanoparticle-based drug formulations; safety issues of nanofabricated materials; safe-by-design approaches; lack of information on exposure to nanomaterials; health-risks of nano fertilizers or food additives; public perception of nanoparticles as harmful in healthcare
8. Lack of information which contributes to the hesitance of the public about nanomaterials.
9. Disposal and recycling of new materials; end-of-life for nanomaterials and nanoproducts.
10. Uncertainty surrounding safety-related issues; lack of specific regulations and standards for risk assessments and risk management; regulatory framework too slow relative to the speed of progress in nanotechnology.
11. Lack of a unified strategy at different levels of education; retrain and continually train skilled workers; lack of entrepreneurship and innovative management skills; lack of soft skills for researchers/workers who operate in transdisciplinary teams; Bridging the gap on Tech Transfer.
12. Difficulty on introducing a new material (i.e., nanomaterial) in an already existing manufacturing/fabrication process.

Through a reorganization and integration of the less relevant clusters, we have reached the preliminary action plan reported within this document. This change was needed to switch from an issue-oriented perspective (challenges) to an action-oriented perspective (research, innovation, and coordination actions) according to the following tentative actions/topics:

- 1. Mass-production techniques for sustainable nanofabrication: volume scaling and product testing (IA)

- 2. Digitalisation as enabler of optimized nanofabrication production practices (RIA)
- 3. A nano-regulation framework: streamlined EHS assessment for nanoparticle-based delivery systems, formulations, and additives (CSA)
- 4. Multi-level education strategy (upskill, reskill, and novel education curricula) for bridging the technology transfer gap from transdisciplinary nanotechnology innovation to entrepreneurialism management (CSA)
- 5. Metrology for reproducible and reliable product quality in high-impact nanotechnology applications (e.g., mobility, health) (RIA)
- 6. Reliable NEMS and MEMS for Key Enabling Technologies: future-oriented and energy efficient nano-sensors and -systems for high-impact applications (e.g., mobility, health, and environment) (IA)
- 7. Establishing a structured safe- and sustainable-by-design (SSbD) approach for the European nanomaterial ecosystem (CSA)
- 8. Living materials for multi-function devices (RIA)

The following paragraphs discuss the listed actions in detail.

1.1 Mass-production techniques for sustainable nanofabrication: volume scaling and product testing (IA)

Expected outcomes:

- Increase process reproducibility, yield, energy efficiency, and scalability for a broad range of valuable nanofabrication processes, particularly the ones with positive benefit-to-risk ratio applications (e.g., health, mobility, etc.);
- Reduce the environmental footprint of production.
- Define process operational guidelines and quality criteria that are able to ensure product performance stability in upscaling processes.
- Circular strategy contribution to improve health, safety, and environmental product performance via the encouragement of responsible sourcing strategies
- Develop contactless characterization and non-destructive tests for a seamless production-line integration to support the development of production-line digital-twin models.
- Identify cost-effective strategies and up-to-date methodologies for metrology adoption and just-in-time rectification.
- Provide business opportunities for SMEs by linking the demand and supply of new services/products, as well as supporting their development/transformation to increase production volume.
- Promote process-related safe-by-design approaches (i.e., engineering controls).
- Assess sustainability over its three pillars (i.e., economic viability, environmental protection, and social equity).

Scope:

Actions should develop solutions through industry- and user-driven interdisciplinary consortia covering processes and operational guidelines, aiming to increase process reproducibility, yield, and scalability in a broad range of nanofabrication production lines.

Actions should develop solutions able to empower each and all the production chain steps in a holistic way, resulting in a systemic design advancement of the production processes developed up-to-now in the nanofabrication sector. This action should consider the exploitation of metrology and contactless characterization techniques to support product standardization and just-in-time product rectification, where defects are present. The developed techniques should target the development of cost-effective, advanced characterization techniques, supporting a better-quality assessment and facilitating process rectification.

Proposals submitted under this topic should include a business case and exploitation strategy. For TRLs 6-7, a credible strategy to achieve future full-scale manufacturing in the EU is expected, indicating the commitments of the industrial partners after the end of the project.

Actions should facilitate the market uptake of solutions developed through industry- and user-driven multidisciplinary consortia covering the relevant value chain. In this process, standardisation aspects need to be considered and updated periodically. Market adoption of safe- and sustainable-by-design practices need to be promoted throughout the whole production life cycle (including packaging), when developing their solution.

Proposals submitted under this topic should include a preliminary list of concrete sustainability key performance indicators based on LCC, LCA, Safe by design evaluation.

Actions should justify the relevance of selected pilot demonstrations in different locations within the EU (and also outside, if there is a clear added value for the EU economy, industry, and society).

Actions should also contribute to improve the awareness of relevant external stakeholders and the general public across the EU about the importance of nanotechnology for society, the challenges faced in reaching stable processes for nanomaterial products upscaling and about proposed solutions supporting societal acceptance of and trust in nanomaterials and their production in the EU.

Actions should envisage clustering activities with other relevant selected projects for cross-project co-operation, consultations, and joint activities on cross-cutting issues and sharing of results as well as participating in joint meetings and communication events. To this end proposals should foresee a dedicated work package and/or task and earmark the appropriate resources accordingly.

Specific topic conditions:

Activities are expected to achieve TRL 6-7 by the end of the project.

1.2 Digitalisation as enabler of optimized nanofabrication production practices (RIA)

Expected outcomes:

- Development of an advanced process-analysis modelling services through predictive techniques for an efficient scale-up to production scale
- Development of cost-effective AI-enabled systems to facilitate just-in-time production rectification and to correlate multiple metrology techniques, which are currently not directed at addressing nanosized features, to adapt them to nanomaterials (e.g., indirect measurement of nanoparticles via regression of multiple macroscopic features to a specific nanoscale particle trough the correlation of nanofeatures to micro/macro scale features).
- Develop a standardised database of digital models, collecting past experiences to direct the future product and process upscaling.
- Identify cost-effective strategies for exploitation of material characterization in production modelling practices.
- Define operational guidelines directed at the standardization in production processes characterization.
- Provide business opportunities for SMEs by facilitating the sharing of production practises, hence fostering their digital transformation.

Scope:

Actions should develop solutions through industry- and user-driven interdisciplinary consortia covering processes and operational guidelines, aiming to increase process reproducibility, yield, and scalability in a broad range of nanofabrication production lines.

Solutions to empower the production chain in a holistic way, resulting in a systemic design and modelling advancement of current nanofabrication processes have to be developed. This action should consider the exploitation of metrology and contactless characterization techniques, with a particular attention for non-destructive ones, as key enablers of

production chain digitalization and just-in-time AI-enabled production rectification. The development of such techniques should also support the estimation of production stability trough predictive modelling of process upscaling.

Actions should favour cross-dissemination of successful experiences in the adoption of metrology and result in FAIR guidelines to allow transparency and transferability of industrial experiences across the nanofabrication processes (for example, in the development of digital twins). In relation to the former, actions should also contribute to the development of the industry 5.0 digitalization roadmap and foster cross-collaboration between the process upscaling and the EHS modelling trough the identification of common goals.

Actions should encourage new forms of cooperation across the entire value chain and consider the whole product life cycle as well as the safe handling of NMs along the whole production process and the definition and regular update of best practises.

Proposals submitted under this topic should include a business strategy. For TRLs 3-5, a credible strategy to achieve in a long-term perspective further improvement towards higher technology readiness level is expected, indicating the interest of the industrial partners after the end of the project.

Actions should also contribute to improving the awareness of relevant external stakeholders and the general public across the EU about the importance of nanotechnologies for society, the challenges faced in reaching stable processes for nanomaterial products upscaling and about proposed solutions which could help to improve society's acceptance of and trust in nanomaterials and their production in the EU.

Actions should envisage clustering activities with councils (such as European Materials Modelling Council, EMMC, or European Society for Composite Materials, EECM) and other relevant selected projects for cross-projects co-operation, consultations, and joint activities on cross-cutting issues and share of results as well as participating in joint meetings and communication events. To this end proposals should foresee a dedicated work package and/or task and earmark the appropriate resources accordingly.

Specific topic conditions:

Activities are expected to start at TRL 3 and achieve TRL 5 by the end of the project.

1.3 A nano-regulation framework: streamlined EHS assessment for nanoparticle-based delivery systems, formulations, and additives (CSA)

Expected outcomes:

- Harmonization of current Environmental Health and Safety (EHS) approaches and improvement of their robustness, whilst keeping in mind the easiness of implementation, to facilitate the development of standards.
- Contribute to the development of current and future standards, involving standardisation agencies.
- Assessment and modelling of the occupational risks related to the manufacture of nanomaterials.
- Assessment and modelling of the user and environment risks related to consumption of nano-enabled products over their whole life cycle.
- Promote the use of AI/ML in predictive toxicology to iteratively improve QSAR models with experimental data (HTS, HCS).
- Promote the live process of collecting high-quality data that fit in an AI/ML model (e.g., FAIR compliant, accurate data, etc.).
- Development of a structured communication campaign addressing public perception about the risks of nanoparticle-based delivery systems.
- Development of strategies for the adoption of metrology to aim at fully integrated quality assurance.

Scope:

Actions should make use of existing OA database of the exposure data related to nanomaterials, analysing the key information for the assessment of nanomaterials (e.g., particle size, structural allomorph, etc…).

Actions should provide a critical analysis on EHS risks related to nanoparticles manufacture (e.g., intentional/unintentional emissions, airborne particles, direct/indirect exposure, etc…). Where a direct assessment would not be viable, modelling and data extrapolation techniques should be envisaged to deliver a preliminary evaluation of the material hazards and hazard reduction procedures to be adopted (e.g., real-world hazard scenarios). Each assumption should be confirmed by on-site EHS risk analysis when it becomes possible.

Actions should collaborate with relevant authoritative bodies in the nano-safety cluster (e.g., European Partnership on Metrology, EURAMET) to facilitate the transition towards a harmonized and robust assessment process. Actions should follow an open collaborative strategy to allow for a transparent standardization process and justify the relevance of the adopted assessment approaches with respect to alternate ones. Inclusion of industrial stakeholders on current field developments should be envisaged to favour compliance and acceptance of the regulation requirements to access the market.

Actions should promote the exchange of good production practices amongst related industries, favour the adoption of standardised, market-ready safe-by-design approaches, and raise awareness on the already widespread use of nanomaterials in common consumer applications (e.g., food, drug, fertilizers, additives, etc.) and their valuable applications, and address about the complexities and uncertainties of nanomaterials (e.g., biomagnification, chronic exposure, trace materials, direct/indirect chronic exposure, complex matrices nanomaterials, low-dose/trace materials exposure). Actions should contribute to communicate the EU effort in being a pioneer in H&S regulatory activities (e.g., REACH regulation). Actions should envisage clustering activities with other relevant selected projects for cross-projects co-operation, consultations, and joint activities on cross-cutting issues and share of results as well as participating in joint meetings and communication events. To this end proposals should foresee a dedicated work package and/or task and earmark the appropriate resources accordingly.

Actions should also contribute to support the improvement of the wider public perception on nano-topics allowing for the direct adoption of nano-enabled technologies in particular for nanoparticle-based delivery systems.

Specific conditions:

To achieve the expected outcomes, and safeguard the Union's strategic interests, regulatory bodies should take part to the consortium with co-participation to such projects of industrial partners, which may enable a faster adoption of the developed standards.

1.4 A Multi-level education strategy (upskill, reskill, and novel education curricula) for bridging the technology transfer gap from transdisciplinary nanotechnology innovation to entrepreneurialism management (CSA)

Expected outcomes:

- Establish an international roundtable on educational standards aiming at current nanomaterials needs and standards.
- Create an open-access model curriculum to direct education on nanofabrication at all education levels, from schools, to academia, as well as for technician work force.
- Define an implementation strategy, internationally shared, of the identified educational goals.
- Development of virtual learning courses and exchange programs for the lifelong training of current workers.
- Development of interdisciplinary trainings focused on fostering innovation and entrepreneurialism management.
- Educate through several channels the wider public about nanoscience (e.g., internet, general education curriculum).

Scope:

Actions should develop a unified open-access model curricula. Actors should be engaged from both education and nanofabrication ecosystems (e.g., academia, educators, scientists, engineers, and high school teachers) to identify and overcome gaps present within the current model curriculum. The developed curricula will become an enabler for new training opportunities with a transdisciplinary approach, focused on the nanotechnology/fabrication ecosystem. The training opportunities identified should be addressed at all education levels, and lifelong training activities incentivised (e.g., accreditation/certification of the trainings, study exchange programmes, business translation advisory boards, junior researchers mentoring programmes). Actions should also contribute to the education of the general population to nanotechnologies and the associated risks whilst promoting sustainable nanofabrication to young generations of researchers.

Actions should develop an organized database of the trainings with a simple and effective filtering and sorting system. The courses within such database should be monitored for content and kept up to date with current state-of-the-art

developments. The best practices and experiences gathered by the trainings performed by federations and interest groups should be collected and to support future training development and allow for training benchmarking activities.

Actions should be able to cross-benchmark current best practices and training experiences and provide feedback to further develop effective learning experiences for lifelong education. Activities should also foster collaboration between local institutions and industries or professional societies to promote educators' professional development by offering opportunities for visiting cutting-edge nanofabrication research and technology centres.

Actions should further contribute to develop shared educational standards (e.g., ASTM International Education Standards) and promote the fostering of transdisciplinary skills of nanofabrication researchers and workers in the translation of nanotechnologies to added value products. Employers' participation should be envisaged to demonstrate the efficacy of the developed interdisciplinary education activities on process innovation.

The inclusion of transdisciplinary topics in the curricula for the development of skills of nanofabrication researchers and workers concerning nanotechnology innovation, entrepreneurship, and translation of nanotechnologies to added value products should be promoted.

Actions should envisage clustering activities with other relevant selected projects for cross-projects co-operation, consultations, and joint activities on cross-cutting issues and share of results as well as participating in joint meetings and communication events. To this end proposals should foresee a dedicated work package and/or task and earmark the appropriate resources accordingly.

1.5 Metrology for reproducible and reliable product quality in high-impact nanotechnology applications (e.g., mobility, health) (RIA)

Expected outcomes:

- Developing reliable, low-cost, and high-resolution metrology techniques for a trustworthy quality control defining a "zero-defect strategy"
- Developing reliable correlation across multiple, readily available, and cost-effective micro- and macro-scale metrology techniques, to deliver effective assessment of nanosized features by their indirect effects (*e.g.*, viscosity, scattering, stiffness, etc...).
- Development of metrology techniques directed at quality control for specific applications, such as 3D manufacturing technologies
- Development of contactless characterization techniques linked to robust modelling and simulation techniques
- Development of AI-ready interfaces, able to provide the characterization outputs in a standardised format
- Development of solutions for handling missing data by means of machine learning methods and/or simulation
- Promoting investments in the development of cost-effective, advanced characterization techniques and promote the widening of their application range to a broader number of sectors.
- Provide business opportunities, especially for SMEs, facilitating the adoption of shared metrology.

Scope:

Actions should develop metrology technologies easily integrable in the production line (e.g., electrical, optical) allowing for overcoming current technological limits, whilst easing the adoption of shared metrology techniques to all entities, including the ones with a limited budget (e.g., start-ups, SMEs). Actions should place particular emphasis on technologies enabling for radical advancements in the field of nanofabrication (e.g., top-down 3D manufacturing, AI integrated systems) and promote additional private investment in the sector of metrology, to facilitate the development of cost-effective, advanced characterization techniques by translating the developed technologies to the market.

Proposals submitted under this topic should include a business case and exploitation strategy, as outlined in the introduction to this Destination. For TRLs 6-7, a credible strategy to achieve future full-scale manufacturing in the EU is expected, indicating the commitments of the industrial partners after the end of the project.

Actions should address the knowledge gap present within the industry and the academia by establishing means of facilitation for the adoption of up-to-date techniques and methods via trainings dedicated to the dissemination from academia to industry and promoting the adhesion to already existing EU exchange programmes (e.g., MSCA RISE). Actions should also contribute to removing the barriers in accessing highly specialized tools, traditionally used only within the research field. Generation of a digital product twin by its characterization data to enable the direct development of a virtual model to support its nano-characterisation, production, and development processes.

Actions should envisage clustering activities with other relevant selected projects for cross-projects co-operation, consultations, and joint activities on cross-cutting issues and share of results as well as participating in joint meetings and communication events. To this end proposals should foresee a dedicated work package and/or task and earmark the appropriate resources accordingly.

Specific topic conditions:

Activities are expected to achieve TRL 3-5 by the end of the project.

1.6 Reliable NEMS and MEMS for Key Enabling Technologies: future-oriented and energy efficient nano-sensors and systems for high-impact applications (e.g., mobility, health, and environment) (IA)

Expected outcomes:

- Reducing NEMS and MEMS production costs; for example, by improving product upscaling and production efficiency.
- Development of low-cost quality-control manufacturing technologies; for example, by adapting already existing technologies to new applications.
- Improving the cost/quality ratio of reliably produced devices at a high level of precision.
- Overcome product integration barriers by meeting operational requirement conditions.
- Improve the energy management and efficiency via consumption reduction and energy diversification.
- Increase competitive sustainability of SMEs through the uptake of advanced technologies.
- Technology transfer acceleration to market-ready devices by the development of NEMs and MEMs ready out of the box.

Scope:

Actions should further develop NEMS and MEMS by overcoming the current barriers in the implementation of NEMS and MEMS by addressing several issues (e.g., cost/quality, competitiveness against traditional technology, energy management and efficiency, multi-material integration, precision) to allow the integration and operation in real conditions (e.g., advanced energy management).

Actions should develop novel nano-devices and -sensors applicable for several cutting-edge applications especially for health, environment, and mobility sectors, such as cell activity sensing, environmental monitoring sensors, nano-bio interaction, nano-topologies, and nano bio-blocks. Action should meet production and performance reproducibility requirements needed for health and mobility sectors (i.e., nano-sensors), for example addressing the need to reduce energy consumption by improving energy efficiency and complementing it with energy conversion and harvesting. Digital technologies such as Blockchain and AI based approaches could be included as useful assets (not mandatory).

Proposals submitted under this topic should include a business case and exploitation strategy, as outlined in the introduction to this Destination. For TRLs 6-7, a credible strategy to achieve future full-scale manufacturing in the EU is expected, including interest and potential commitments by the industrial partners after the end of the project.

Actions should facilitate integration of the developed mechanical nano-sensors into final products (e.g., health and mobility) and assay for potential applications in the nanofabrication production-line (e.g., metrology-oriented sensors). An investment's framework for the developed technologies after project end should be also foreseen. Actions should look for synergies with the metrology actions to increase production precision whilst promoting investments in metrology, especially for 3D manufacturing technologies. The developed technologies should meet product trustworthiness and reliability expectations of customers.

Actions should envisage clustering activities with other relevant selected projects for cross-projects co-operation, consultations, and joint activities on cross-cutting issues and share of results as well as participating in joint meetings and communication events. To this end proposals should foresee a dedicated work package and/or task and earmark the appropriate resources accordingly.

Specific topic conditions:

Activities are expected to achieve TRL 6-7 by the end of the project.

1.7 Establishing a structured safe and sustainable-by-design (SSbD) approach for the European nanomaterial ecosystem (CSA)

Expected outcomes:

- Strategies for the adoption of safe and sustainable-by-design by industry and SMEs, end-users, regulatory and public authorities, research organisations, and academia
- Provide tiered-guidance system for adopting SSbD approach; Adoption of tailored-approaches adapted to the size of the players (academia, start-up, SMEs, large industries)
- Improvement of cross-KETs activities to provide better integration of safe- and sustainable-by-design in the product development.
- Development of an inclusive approach to implement safe- and sustainable-by-design strategies early in the innovation process, a systematic and standardized risk-analysis assessment and of market-ready approaches; fitting the industry needs and following market products regulations
- Promotion of safe- and sustainable-by-design approaches by the verification/validation of applicability robustness and correctness of tools, models and platform; encourage the development of NEP passport to tack/trace ENMs all along their value chains
- Monitoring of material streams to identify circular approaches for by-products as well as for products
- Improvement of EU nanofabrication competitiveness through market-ready safe- and sustainable-by-design approaches.

Scope:

Actions should contribute to develop open standards and standard operating procedures repositories for standardized safe-by-design development procedures, combining both experimental and theoretical approaches. Actions should facilitate the harmonisation in the data collection for the development and sharing of successful experiences in safe-by-design product and process development, considering all the actors of ecosystem. Actions should address safety aspects as they are important for the market uptake of nanomaterials.

Actions should also contribute to the analysis on the use nano-enabled materials along the whole process life cycle, assessment of the risks at all stages, and integration of the impact of the nanoparticles character on the final solution by setting up appropriate collaborations with applicable actions.

A variety of different use cases and be developed to be effectively adopted by anyone in the early stages of the product development process need to be covered. Actions should support the adoption of such standardised procedures by a wide range of users, making them accessible to LEs and SMEs. Actions should seek for validation of the developed procedures by collaborating with the evaluation process users. Process validation could be obtained from direct validation and/or cross-validation of computational and experimental workflows, allowing for a wider scope for the repository procedures collection process.

Actions should envisage clustering activities with other relevant selected projects for cross-projects co-operation, consultations, and joint activities (*e.g.*, AI Nano annotation DataUnion resource) on cross-cutting issues and share of results and benchmarking tools as well as participating in joint meetings and communication events. To this end proposals should foresee a dedicated work package and/or task and earmark the appropriate resources accordingly.

1.8 Reliable Living materials for multi-function devices (RIA)

Expected outcomes:

- Contribution to regenerative medicine strategies and in vitro models will benefit from multi-scale and multi-function devices integrating complex living materials

- Development of improved biomimicry of intended biological systems and increased production speed
- Reaching the possibility of monitoring or stimulating different biological events and tissues at a time
- Increase of high-tech European competitiveness by commercializing multi-scale and multi-function devices and related materials and technologies

Scope:

Actions should address new bio-fabrication technologies able to work with multiple materials, which results in enhanced properties of the finally produced devices

Actions should address technologies such as volumetric bioprinting allowing the fabrication of multi-scale objects with fast speed of fabrication and high resolution

Actions should address the optimization of those technologies through innovative complex multi-scale modelling and digital twin approaches.

Actions should envisage clustering activities with other relevant selected projects for cross-projects co-operation, consultations, and joint activities

Projects should build on or seek collaboration with existing projects and develop synergies with other relevant European, national, or regional initiatives, funding programmes and platforms.