LIFE CYCLE ANALYSIS of NANOPARTICLES

Risk, Assessment, and Sustainability

Edited by

ASHOK VASEASHTA

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ASHOK VASEASHTA, Ph.D.

Director of Research
International Clean Water Institute and Institute for Advanced Sciences Convergence
NUARI, Northfield, Vermont USA

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In fond memory of my dog—QD,
for his amazing sensing capability,
risk assessment methodology,
survival skills—all executed with
a great sense of dignity and humor

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Preface

MICROCOSM to macrocosm, eco-design, eco-efficiency, eco-friendly, green-cities, zero carbon foot print, environmentally friendly systems, and the triple bottom line are the vernacular of a sustainable future. On one hand enhanced use of technology and information, and modern amenities simplify our lives and are considered positive outcomes for a society, while on the other hand, these practices increase demands on essential services. Optimal use, reuse, recycling, and discarding require a modified way of living that promotes sustainable outcomes. Since human beings and natural resources must co-exist, it is quintessential to transform the technology savvy outlook to assure future sustainability. These fundamental transformations necessitate that sustainability must be considered as an integral part of our routine as we design and develop the systems and the latest technologies that enable our current way of life.

The concepts of sustainability and life-cycle analysis are interconnected, yet challenging to delineate. This book on "Life Cycle Analysis of Nanoparticles—Risk, Assessment, and Sustainability" was originally aimed to cover the life-cycle analysis of engineered nanomaterials in products currently in use and how future trends in enhanced use of nanomaterials will impact the research and commercial production. It became evident that the details of the full life-cycle, i.e. cradle-to-grave trans-configuration of a product will not be evident without additional information, such as mathematical modelling of constituent materials, components and products, dispersion assessment with sophisticated sensors, and environmental impact. It is a representative problem,

widely recognized as "*The Collingridge dilemma*", i.e. there is always a trade-off between knowing the impact of a given technology and the ease of influencing its social and innovation trajectories. Sustainability can be achieved only through analysis, supplemented by technologies such as minimization, risk reduction, and recycling.

The concept of "Life-ycle Thinking" entails a holistic approach to the product, process or service under consideration and comprises inventory of all the inputs, outputs and impacts at each stage of the life-cycle. This being the basis, this book assumes that to be considered sustainable, nanomaterials must be subject to life-cycle analysis. However, due to the complexities of applying a full life-cycle analysis (LCA) to a spectrum of nanomaterials, including a dearth of mathematical models, this book focuses on introducing selected life-cycle concepts and showing how they are applied to nanomaterials. This book introduces the life-cycle concept in the framework of risk, assessment, and characterization that will be extended in subsequent versions to include details of the raw materials, material production, manufacturing, distribution, use and end-of-life treatment. Furthermore, since sustainability requires considerations of design beyond the traditional way points of view, there is always a need to provide a balanced analysis of how a sustainable vision may be attained, since sustainability is considered as "a relative" term. The chapters are designed to systematically describe how nanomaterials, system design, environment, and professional approaches and ethics address this concept from a designer's perspective. Examining present and future issues facing practitioners, the book provides a necessary context for sustainable development design from a system design perspectives.

The text starts with basic definitions of sustainability and locates them in the framework of nanomaterials. It then presents the basic life-cycle concept, such as assessment, characterization, and risk analysis as these relate to engineered nanomaterials and nanoparticles, with the goal of showing how these tools can contribute to a view of nanomaterials as sustainable. Models, environmental fate and societal issues are considered. Further chapters describe the real and perceived risks of nanomaterials and how these are measured, followed by chapters on advanced sensors. Deployment of multi-analyte and real-time sensing devices and sensor networks can provide more accurate data for more realistic exposure information, thereby enabling better and more holistic environmental assessments. More robust and accurate environmental assessments will in turn yield more accurate analyses and improved

evaluation of potential impacts. Since sustainability is linked to design, the book presents how nanomaterials and their proper, i.e., ethical, use are viewed from a design perspective. The approach looks broadly over the entire life cycle of a compound, product or process to consider both direct and indirect effects.

This book delineates the ideas and principles that form at the very foundation of the topic of assessing risk of a disruptive technology. The use of nanotechnology has provided many pathways towards a sustainable future in terms of lightweight, biodegradable, and biocompatible materials providing many useful applications. Notwithstanding benefits, the unknown interaction of these nanoparticles with humans at the cellular level remains a topic of debate. This further leads to a variety of codes of conduct and associated ethics, and a critical analysis employing existing published codes and the practices that stem from them. It takes a practical approach, discussing applied ethics, and relies upon an understanding of the moral reasoning that supports the ideas and professionalism and an ethical standard of care. Drawing on the author's experience as an engineer and scientist engaged in strategic transformative technologies, this book provides a discussion of the underlying reasoning and approach involved in the challenges confronted by contemporary design professionals. This information can then be distilled into sustainable practices in the future for eco-friendly design in support of green infrastructure and sustainable future.

The purpose of this book is to provide knowledge for engineers, scientists, designers, researchers, and students who are involved in LCA studies, sustainability and green-design. The book starts out with basic definitions and concepts of sustainability in the framework of nanomaterials. The book then introduces the concept of LCA by way of nanomaterials, its modeling and examples in environmental settings. Further chapters describe actual and perceived risk of nanomaterials followed by chapters describing risk characterization by way of advanced sensors. The book then concludes with selected chapters describing applications of nanomaterials from a sustainability standpoint. To keep the scope to the point and concise, only selected chapters are presented here and it is anticipated that the subsequent volumes will have a further discussions adding to the full spectrum of techniques and applications.

Ashok Vaseashta
Washington, D.C., Herndon, VA
and Northfield, VT USA

About the Contributors

ASHOK VASEASHTA received a PhD from the Virginia Polytechnic Institute and State University, Blacksburg, VA in 1990. Before joining as the Director of Research at the Institute for Convergence of Information, Science, Technology, and Knowledge (formerly Institute for Advanced Sciences Convergence) and International Clean Water Institute, he served as a Professor of Physics and Physical Sciences and Director of Research at the Nanomaterials Processing and Characterization Laboratories, Graduate Program in Physical Sciences at Marshall University. Concurrently, he holds a visiting professorship at the 3 Nano-SAE Research Centre, University of Bucharest, Romania and chaired professorship at the Academy of Sciences of Moldova, Chisinau, Moldova. He was visiting scientist at the Helen & Martin Kimmel Center of Nanoscale Science at the Weizmann Institute of Science, Israel. In 2007–08, he was detailed as a William C. Foster fellow to the Bureau of ISN at the U.S. Department of State working with the Office of WMDT and FCM programs. He served as Franklin Fellow and S&T advisor for the office of VTT/AVC in the Bureau of Arms Control Verification and Compliance at the U.S. Department of State. He is a fellow of the American Physical Society, Institute of Nanotechnology, and New York Academy of Sciences. He was awarded a Gold medal by the State Engineering University of Armenia for his contribution to Nanotechnology. In addition, he has earned several other fellowships and awards for his meritorious service including the Marshall University 2004/2005 Distinguished Artist and Scholar award. His research interests include counter-terrorism; advanced and nano materials for

development of chemical-bio sensors/detectors; water safety and security; environmental pollution monitoring, detecting and remediation; and green nanotechnology. He authored over 230 research publications, edited/authored five books on nanotechnology, presented many keynote and invited lectures worldwide, served as the NATO Project Director of five NATO ASI/ARW, multi-year SPS program, and co-chair of an IS-NEPP conferences. He led the U.S. position on Nanotechnology in High Technology Coordination Group to joint U.S. and India delegation. In addition, he served as a member of the U.S. Department of Commerce, NIST, and ANSI delegation to the U.K., representing the U.S. position on Standards in Nanotechnologies at the inaugural meeting of the ISO/TAG to TC-229. He is a member of NATO-SET-040, an exploratory team panel investigating security and surveillance applications of nanotechnology. He serves as an expert counsel to UNESCO, ObservatoryNANO, and COSENT—South-east Consortium on Nanotechnologies on NANO-Science and Technologies. He is an active member of several national and international professional organizations.

Mary Ann Curran is an internationally-recognized LCA expert. After 32 years of federal service as a research chemical engineer with the U.S. Environmental Protection Agency, Dr. Curran is working independently as an LCA and sustainability consultant. Through her 20+ years of LCA research, networking, and publishing, she developed an in-depth knowledge of LCA methodology and application and created an extensive network of LCA researchers and practitioners worldwide. Dr. Curran's research activities included the development of LCA methodology, the performance and review of life-cycle case studies, planning life-cycle workshops and conferences, and the development of life cycle data and resources. As of 2013, Dr. Curran is Editor-in-Chief of the International Journal of Life Cycle Assessment, along with Prof. Walter Klöpffer. Dr. Curran has authored and co-authored numerous papers and book chapters which address the LCA concept and its applications, and created the LCA Handbook as editor and co-author (published by Scrivener-Wiley in October 2012). She has presented EPA's activities in LCA-related research at technical meetings across the U.S. and in Europe, South America, South Africa, Asia, and Australia. Dr. Curran studied Environmental Management and Policy at Lund University, Lund, Sweden (MSc 1996); and earned a Doctor of Philosophy degree in Erasmus University's International PhD program on "Cleaner Products, Cleaner Production, Industrial Ecology and Sustainability"

for her thesis entitled "Development of Life Cycle Methodology: A Focus on Co-Product Allocation" (2008). Dr. Curran is a Fellow of the American Institute of Chemical Engineers (AIChE).

SRDJAN GLISOVIC is an Associate Professor at the University of Nis where he teaches Industrial Ecology, Societal Development and the Environment, Life Cycle Analysis, and Project Management. He graduated in engineering from University of Nis and defended his doctoral dissertation at the University of Novi Sad (environmental science). His research interests are: Product-Centric Environmental Management, Industrial Ecology, Sustainable Design of Industrial Products, and Industry-Society Relationships and Consumption–Environment. Dr. Glisovic is the author of over 50 scientific papers published in national and international publications and conference proceedings in the areas of Sustainable Design and Environmental Management. He authored the chapter "Sustainable Production and Consumption" within the monograph "Road Signs Toward Sustainable Development", under auspices of the Ministry of Science and Technology, Republic of Serbia. Dr. Glisovic was appointed National Contact Person for international project "Netherlands—West Balkans Environmental Network" under auspices of Ministry of Finance, The Kingdom of the Netherlands, as well as National Coordinator of the international joint doctoral studies "EteCoS3" under auspices of the Erasmus Mundus project sponsored by E.U. He was member of research teams on various projects under auspices of Serbian Ministries of Science and the Environment. He is fluent in Norwegian, English, Spanish and Italian. Dr. Glisovic has been appointed Municipal Support Expert under the European Commission sponsored program MSP-IPA 2007, Chief Lecturer of the International Summer Schools organized by the Board of European Students of Technology and Editor of the scientific journal "Safety Engineering". Dr. Glisovic was also Invited lecturer at International Training Workshops on Environmental and Occupational Health in the framework of the project "Training and Research in Environmental Health in The Balkans (TREHB)", under auspices of NIH/Fogarty International Center and the Institute of International Health, Michigan State University, USA. Dr. Glisovic is laureate of "Sustainable Development and Environmental Leader for Tomorrow" award by "Environmental Ambassadors" and Royal Dutch Embassy. At present he is head of The Centre for Distribution of Development Strategies at the Faculty of Occupational Safety, University of Nis.

URMILA M. DIWEKAR is currently President of the Vishwamitra Research Institute, a non-profit research organization that she founded in 2004 to pursue multidisciplinary research in the areas of Optimization under Uncertainty and Computer aided Design applied to Energy, Environment, and Sustainability. From 2002-2004, she was a Professor in the Departments of Chemical Engineering, Bio Engineering, and Industrial Engineering, and in the Institute for Environmental Science and Policy, at the University of Illinois at Chicago (UIC). From 1991–2002 she was on the faculty of the Carnegie Mellon University, with early promotions to both the Associate and the Full Professor level. In chemical engineering, she has worked extensively in the areas of simulation, design, optimization, control, stochastic modeling, and synthesis of chemical processes. Recognizing uncertainties in real world processes, she started working in 1991 on stochastic modeling, efficient methods for uncertainty analysis, and optimization under uncertainty. These led to productive contributions in fields as diverse as advanced power systems, sustainability, environmental management, nuclear waste disposal, molecular modeling, pollution prevention, renewable energy systems, and biomedical engineering. In 1999 she founded the Center for Uncertain Systems: Tools for Optimization and Uncertainty (CUSTOM) to foster interactions between various industries, national laboratories and various academic disciplines. She is the author of more than 135 peer-reviewed research papers, and has given over 300 presentations and seminars, and has chaired numerous sessions in national and international meetings. She has been the principal advisor to 35 Ph.D. and M.S. students, and has advised several post-doctoral fellows and researchers. She has published four books and also written 12 book chapters. Professionally, she is active in the AIChE, having served as a Member of the Executive Committee and as a Director in both the Computers and Systems Analysis division and in the Environmental division.

LISE LAURIN founded EarthShift in 2000 to support businesses in their endeavor to reduce environmental impacts. With EarthShift, she has focused on Sustainability Return on Investment (S-ROI) and Life Cycle Assessment (LCA) as tools for measuring sustainability. She is a pioneer in S-ROI, having broadened the scope from the original Total Cost Assessment methodology to include benefits and impacts to society, and in particular how a decision can be adapted to be a win-win-win solution for all stakeholders. Her focus is on building capacity in indus-

try and government, providing software tools, training, and consulting. Lise works with the AIChE on further development of the S-ROI methodology. She is the Vice President of the Sustainability Conoscente Network, is a member of the board of advisors of the American Center for Life Cycle Assessment and a member of the SETAC LCA Advisory Group Steering Committee. She brings to this effort over 20 years in industry and holds a BS in Physics from Yale University.

ANTONIETTA M. GATTI received a degree in Physics and a PhD in Bioengineering at the University of Bologna. She served as lecturer at the Universities of Ferrara and Bologna. At the University of Modena and Reggio Emilia she was the chief of the Center of Biomaterials and was professor of Dental Materials at the College of Dentistry. While at the Faculty of Biotechnology she taught Biomaterials from 1979 to 2011. She was Coordinator of Italian (INESE, BATNAN, VENAM) and European (Nanopathology, DIPNA) Projects, mostly addressing nanotoxicology, nanopathology and nano-ecotoxicology. At present she is an associate professor at the National Council of Research of Italy at the Institute of Science and Technology of Ceramic Materials (ISTEC); professor of Cytometry at the University of Urbino (Italy); and principal investigator at Nanodiagnostics, a SME she founded in 2004. The Laboratory specializes in analyses of biological or organic matrixes to identify micro and nanosized pollution (humans, animals, vegetables, food). Concurrently, she holds an honorary visiting/distinguished Professorship at the Institute for Convergence of Information, Science, Technology and Knowledge (ICISTeCK) and International Clean Water Institute (ICWI). In 2012 she was awarded as an International Fellow of the Union of the Societies of Biomaterials and Engineering for her work on Biomaterials and Nanotechnology. She was a Smart-Filter at NASA and was selected for writing a report on Nanofood and its safety. She authored over 220 peer-reviewed articles, authored one book on Nanopathology, and chapters in various books, presented many keynotes and invited lectures worldwide (USA, Australia, UK, Norway, France, Spain, Turkey, Japan, China, etc.). In addition, she served as a consultant to three National Commissions on Depleted Uranium and Related Diseases and as a member of the Italian Scientific Committee on the Control and Prevention of Soldiers' Diseases of the Italian Ministry of Defense. She belongs to the European Committee called Nanosafety Cluster, serves as reviewer in some editorial boards of scientific journals and is an active member of several national and international (EC,

ECOS) professional organizations. Her work of Research is addressed to the impact of the nanoparticles on humans, animals and environment. She was active in studying the diseases of the 9/11 survivors, rescue and sanitary workers and firefighters who were exposed to dust from the Twin Towers terrorist attack.

GANNA O. KHARLAMOVA graduated from Taras Shevchenko National University of Kyiv, Ukraine and received her Ph.D. degree. Currently she is an associate professor at Taras Shevchenko National University of Kyiv. She has produced more than 130 publications, including 5 tutorials, textbooks and manuals, and 6 books. She took part in approximately 100 All-Ukrainian and International scientific-&-practical conferences, in FP7 Information & Brokerage Event on Environment (Including climate change), 21st OSCE Economic and Environmental Forum: Second Preparatory Meeting, in more than 20 NATO ASI or NATO ARW. She has participated in a 3-year initiative on "The Economics of the Firm" (which includes a series of summer schools and workshops), held by EERC (The European Economic Research Consortium). Research member of the Research Center in Political Science, International Relations and European Studies—a research unit of the Department of International Relations, Political Sciences and European Studies, Lucian Blaga" University of Sibiu, Romania. She serves on the editorial board and is a peer-review member for more than 10 international scientific journals. Her fields of interest include environment and ecological safety, Ecoterrorism, state security, investment, human capital estimation, macro-economic forecasting, risk analysis, and socio-economic modeling. Her research also includes analysis of nanomaterials, modelling and forecasting of impact on environment and human health.

OLEKSII KHARLAMOV graduated from Lomonosov Moscow University, Department of Chemistry, Moscow, Russia and received his PhD in Chemical Sciences. Currently, he is the Head of Laboratory of Nanochemistry in the Institute for Problems of Materials Science of National Academia of Science, Kiev, Ukraine. His research activity is related to nanochemistry of boron and carbon as well as their compounds. He has authored 190 research publications.

ARZUM ERDEM GURSAN received a Bachelor in Pharmacy degree from Ege University, Izmir, Turkey in 1993. She received the master