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The Use of Environmental, Health and Safety Research in Nanotechnology Research

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Environmental, health, and safety (EHS) concerns are receiving considerable attention in nanoscience and nanotechnology (nano) research and development (R&D). Policymakers and others have urged that research on nano's EHS implications be developed alongside scientific research in the nano domain rather than subsequent to applications. This concurrent perspective suggests the importance of early understanding and measurement of the diffusion of nano EHS research. The paper examines the diffusion of nano EHS publications, defined through a set of search terms, into the broader nano domain using a global nanotechnology R&D database developed at Georgia Tech. The results indicate that nano EHS research is growing rapidly although it is orders of magnitude smaller than the broader nano S&T domain. Nano EHS work is moderately multidisciplinary, but gaps in biomedical nano EHS's connections with environmental nano EHS are apparent. The paper discusses the implications of these results for the continued monitoring and development of the cross-disciplinary utilization of nano EHS research.

Keywords: Nanotechnology, Environmental, Health, and Safety, Risk.

1. INTRODUCTION

Investment in nanoscience and nanoengineering (nano) environmental, health, and safety (EHS) research is among the fastest growing areas of overall nano research and development (R&D) public investment. The US National Nanotechnology Initiative (NNI) allocated $350 million to nano EHS research from 2005–2009. In fiscal year 2010, the federal nano EHS budget is nearly triple the size of what it was in 2005, compared to a 37% increase in the overall NNI budget. EHS R&D investment comprises more than 5% of the fiscal year 2010 NNI budget, and a policy target of 10% of the NNI budget allocated to nano EHS has been discussed.8,9 The President’s Council of Advisors on Science and Technology added a special separate addendum report to its second review of the NNI focused on nano EHS issues and NNI investments in this area.8 There have been significant levels of attention in other countries on nano EHS concerns. For example, the UK Royal Commission on Environmental Pollution published a report ‘Novel Materials in the Environment: The Case of Nanotechnology’ in November 2008. It spotlighted nanotechnology risks and recommended stronger governance frameworks for addressing the area.6 Meanwhile, the Organisation for Economic Cooperation and Development (OECD) has established guidelines,5 coordination mechanisms (such as Working Party on Manufactured Nanomaterials), and programs for exchanging nano EHS information.

Why is all this EHS activity occurring in the nanotechnology R&D domain? It is widely accepted that EHS research and testing is important to ensure safety and to understand and minimize risks of exposure from novel nano materials and applications. The turbulent experience of EHS concerns affecting the development and acceptance of some other new technologies, such as genetically modified organisms (GMOs), underscores this. In response, the US Government has developed a strategy for nanotechnology-related EHS research to focus EHS specialists in key nano EHS research areas and to coordinate nano EHS efforts across agencies.2 There is an explicit role for funding and developing researchers with specialized backgrounds in and knowledge of EHS research methods in the nanotechnology domain to address safety, risk and exposure issues.

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Additionally, in the US, there are requirements to proactively consider the societal implications of nanotechnology in parallel with scientific and economic objectives. The 21st Century Nanotechnology Research and Development Act (P.L. 108–153) was passed in 2003 with a mission to integrate societal concerns into nanotechnology R&D. Section 2(b)(10) of this act establishes a societal implications research program, requires nano research centers (NSECs) to address societal implications, integrates societal concerns with nanotechnology R&D, and seeks to ensure that advances in nanotech lead to quality of life improvements for all. Environmental concerns are prominent among the societal aspects raised in this legislation along with ethical, legal, and other concerns. The Act and the subsequent NNI Strategic Plan both highlight the importance of markets and user input, and linkages to feedback loops, the criticism in recent years for ignoring feedback loops, the rearrangement of the nature and timing of testing, characterization, risk evaluation, and toxicity assessment activities. In the conventional linear research and innovation model—which posits that discovery moves through various categories from research, development, production, and use in a sequential manner—EHS activities typically take place in the later stages once applications have been developed. This model has been increasingly criticized in recent years for ignoring feedback loops, the role of markets and user acceptance, and linkages to broader systems. The high risk nature of many emerging technologies intensifies this critique, leading to calls for EHS activities to be placed earlier in the process and to be integrated with discovery. This new conceptualization of the importance of positioning EHS activities alongside nano S&T research activities has been recognized by nanoscientists themselves. For example, Vicki Colvin, Professor and Executive Director of the Center for Biological and Environmental Nanotechnology, testified before the House Committee on Science in 2007 that “there is an urgency to nano-EHS research that affects the entire NNI investment.” Likewise, Dr. Lee Ferguson, with the Department of Chemistry and Biochemistry at the University of South Carolina, has stressed the need to tackle the environmental and health impacts of nanotechnology as the technology is developed. He states:

… we cannot afford to wait until nanotechnology is fully developed to begin assessing its risks and hazards to human health and the environment… We have a unique opportunity now—through the NNI we have begun to address the EHS risks of nanotechnology simultaneously with the development of this technology. We have only to look at the lessons learned from PCBs and other legacy chemical contaminants to realize the dangers of waiting until new technologies are mature to assess their environmental and health risks.1

However, the capability to integrate nano EHS work with nanoscience R&D, as well as to advance nano EHS work itself, depends to an important extent on interdisciplinary connections and collaborations. Nanotechnology draws on many scientific and technological disciplines. Porter and Youtie find that nanotechnology publications can be found in multiple locations across the “map of science,” albeit with a concentration in materials science and chemistry.10 Nanotechnology research is not simply an amassing of unrelated disciplinary inquiries. The study shows that research in any one category of nanotechnology often cites research in other disciplines, even though integration scores show that much of science and engineering is comparably interdisciplinary. Focusing on a specific nanotechnology (kinesin molecular motors), Rafols et al. observe that many of the interdisciplinary connections involve sharing of knowledge and standard practices and methods.11 These interdisciplinary aspects of nanotechnology have particular relevance for nano EHS research. The NNI strategy for nanotechnology-related environmental, health, and safety research references the need for methods and characterizations that are reproducible and standardized across disciplines. Similarly, the Royal Commission on Environmental Pollution’s examination of the nano EHS area highlights the significance of cross disciplinary connections between the environmental side of nanotechnology EHS and the medical side:

The research programme should pave the way for much greater interdisciplinary co-operation, including co-operation between those engaged in medical toxicology and those in ecotoxicology, so as to enhance the development of robust test systems and also to act as a catalyst for early warnings from observations on lower organisms to be extrapolated to humans.12

The anticipatory and cross-disciplinary requirements for nano EHS suggest that there is a need for research that assesses the extent of diffusion and disciplinary connections. It is apparent that nano EHS research knowledge is being made available. There are a number of scientific journals which publish articles in the nano EHS domain. Some of these journals are explicitly interdisciplinary (publishing EHS articles alongside articles related to multiple other aspects of nanotechnology). For example, the Journal of Nanoscience and Nanotechnology has published about one hundred articles in the nano EHS domain from 2004 to 2010, with the number increasing by an order of magnitude from the year 2004 when compared with 2009. The most highly cited article in this journal (receiving more than 50 citations in Google Scholar as of 2011).
June 7, 2010) is the Fiorito et al. work “Toxicity and Bio-compatibility of Carbon Nanoparticles,” which provides a summary of research on the biological effects of carbon nanoparticles. The next most highly cited articles (receiving 30 or more citations in Google Scholar as of June 7, 2010) are Ravi Kumar et al., Wei et al., and Sharma et al.

Yet, while there is now a growing body of EHS articles, few studies have systematically examined how that knowledge is used by other scientists engaged in nanotechnology R&D. Among this limited body of research, Ostrowski et al. assessed the scientific literature on EHS, using a broad-based, multi-keyword search strategy. Their results show that the domain is distributed across a range of fields, but it lacks an emphasis on consumer products. Even within the EHS field, risk issues are not always raised. An analysis for the President’s Council of Advisors on Science and Technology’s Third Assessment of the National Nanotechnology Initiative found that only 13 percent of published papers in the International Council on Nanotechnology (ICON) Journal of Nanotechnology Environment, Health and Safety addressed exposure.

In this paper, we seek to add to the understanding of how nano EHS is used by exploring the following two questions. First, we examine the dissemination of nano EHS, asking to what extent has nano EHS research diffused not just within the specialized area itself but also into the broader nano science and technology domain? Second, we focus on the diffusion of EHS knowledge across one particular cross-disciplinary boundary within the EHS domain, by scrutinizing knowledge connections between research on “ecotoxicity” (the fate of manmade nanoscale materials in the environment), and research on “medical toxicity” (hazards to human health).

2. METHODS

To address our research questions, we undertake a bibliometric analysis of scientific publications in the nano EHS domain. The initial building block for this analysis involves developing a definition of what constitutes nano EHS. We begin by developing a typology of nano EHS research output comprised of four categories:

1. Positive implications: EHS research which discusses the potential helpful EHS effects of nano. One example is the article authored by Rice University researchers about the potential of nanorust to remove arsenic from water.

2. Negative implications: EHS research which discusses the potential harmful effects of nano. For instance, some recent research on impacts associated with carbon nanotubes finds lesions similar to those emerging from asbestos in terms of cancerous tumors in mice.

3. Both positive and negative implications: EHS research which discusses both the potential positive effects of nano and also its potential negative implications. This category includes review articles which summarize a particular area of nano S&T research, for example, “Nanoparticles in drug delivery: Biodistribution, therapeutic and toxicological considerations” appearing in Toxicology in 2006.

4. No implications mentioned: The fourth category represents EHS articles that characterize particular nanoparticle or involve fundamental research but are not specific to applications, hence positive or negative effects are not discussed or relevant. This is the modal type of article in the nano R&D domain, where scientists present interesting and novel results at the nanoscale, but do not consider (in that article) whether there are potential EHS implications.

As distinct from the Ostrowski and PCAST bibliometric analyses, our work focuses on the second and third categories (where negative or partially negative concerns are raised). We would anticipate that as nano EHS research diffuses into the broader nano S&T domain, as nano research moves more towards applications, and if scientists in that domain are aware of and attentive to EHS concerns, then the fourth category might diminish relatively in size over time (and there will be a relative growth in the other three categories).

The analysis draws on Georgia Tech’s global nanotechnology database. This database was developed using the search strategy described in Porter et al. to identify publications (and patents) in the nanotechnology domain. The search strategy is based on a multi-stage Boolean approach, and using it we have built data sets of 1.4 million worldwide nanotechnology-related publication records (1990–2008), including more than 508,000 publications listed in the Web of Science’s Science Citation Index (WOS SCI). The focal years for our analysis of nano EHS publications is 2004–2008 as this period approximately covers the ramping up of nano EHS investments in the US and other countries.

Translating our categories of research articles into specific bibliometric terms is a fundamental challenge. Figure 1 illustrates the broad processes we used to develop this domain. An initial set of nano EHS search terms was constructed based on The Virtual Journal of Nanotechnology Environment, Health and Safety, and the US Environmental Protection Agency’s Nanomaterial Research Strategy. We also drew upon the insights from other major national nano EHS strategy documents, discussions with nano EHS experts and funding agency heads, and group exercises with nano scientists and social scientists. Through this process, the synthesized search terms were further tested and refined. Once the searching terms were developed, they were applied in a pilot test to the Georgia Tech global nano database for the year 2008. We tested the validity of applying these terms to the following WOS SCI fields—(1) author’s keywords + keywords...
plus + title phrase + abstract phrase, (2) abstract, (3) title + author’s keywords + keywords plus; (4) abstract + title, and (5) title—by either reading the abstract or (in a few cases) the full papers of the resulting extracted publication subset to determine if the subset was or was not in-domain. The initial application to author or journal keywords or abstract phrases tended to bring in too many out-of-domain publications. In addition to the key term approach, we also tried to seed a search from a core set of publications of highly cited nano EHS scholars (such as Gunter Oberdorster or David Warheit). This specific approach also ran into issues, not only due to difficulties in author identification in publication data, but also because of the need to capture work of general nano scientists as well as nano EHS specialists in light of the focus of our research on the broad diffusion of nano-EHS work. Hence, we found that we needed to incorporate additional search terms to ensure more focused coverage of nano EHS publications. Sets of terms were removed, supplemented, or upgraded with additional validated terms based on trial and error.

From this pilot effort we developed a Boolean search term set which was then more successfully applied to the WOS SCI title field in the Georgia Tech global nano database for the year 2008. The components of the search terms can be broadly classified into three sets. The first set of EHS terms tries to capture explicit nano EHS terms. Keywords in this group include nanotoxicity, nanosafety, and nanoecotoxicity; articles including any term in this set are included. The second set of terms includes broader terms that are conditional on combination to be regarded as the nano EHS research. The third set of terms is “exclusion terms” that cull out-of-domain publications from the database. Most of these exclusion terms refer to the positive or beneficial side of nano EHS as opposed to our focus in this study on the negative impacts. We also considered other terms, such as “fate and transport,” but those terms resulted in too many out-of-domain publications.

Several tests of the results of the search strategy were performed which involved comparing the results of our Boolean search with the results of coding of papers as nano EHS by multiple investigators’ review of paper abstracts (or in some cases, full papers). First, we determined that the 25 most cited papers of nano EHS articles in 2008 were captured by our Boolean search term. Second, the Boolean search was found to capture 75% of the papers that our visual review of abstracts (and some full papers) coded as nano EHS; we could not increase this percentage further by adding more search terms without also adding much more noise to the results. Third, we...
applied this search approach to nano publications in 2007 to confirm its applicability in a different year. The search captured roughly the same percentage of in-domain publications (determined as such by visual review of abstracts and some full papers) as was the case for 2008. Our analysis is thus based on the search approach generated through this process.

3. FINDINGS

Our first set of analyses examines the diffusion of nano EHS publications into the broader nano S&T domain. We wish to understand the extent to which nano EHS research is emerging alongside that of the broader nano S&T domain. The findings suggest that the nano EHS area is still relatively small in size but exhibits fast growth. From 2004 to 2007, the number of publications in the nano EHS area more than doubled in size (\( n = 303 \) nano EHS publications in 2007, \( n = 135 \) in 2004), accounting for 0.5% of the total nano S&T publications in 2007, compared to 0.3% in 2004. The growth rate of nano EHS publications is 124% versus 29% for all nano S&T publications from 2004 to 2007.

Nano EHS publications can also be characterized by the types of nanoparticles which they target. A focus on nanoparticles is important because of the specificity of nano EHS work with respect to nanoparticles and environments such as the previously mentioned work examining the effect of carbon nanotubes on mice or the effect of nanoparticle silver released in water.\(^5\) Nanoparticle targets in this study are measured using references to nanoparticles in abstracts of nano EHS publications. We selected a sample of nanoparticles to examine based on the “list of representative manufactured nanoparticles for testing” as reported in the OECD’s Guidance Manual for the Testing of Manufactured Nanomaterials: OECD’s Sponsorship Programme.\(^5,6,48\) Using this approach, we find that 12% of the 2007 nano EHS publications included one of these listed nanoparticles in their abstracts. Fullerenes (C60) were the most commonly mentioned nanoparticle in the nano EHS data set, followed by carbon nanotubes, silver nanoparticles, and zinc oxide. Comparing this distribution to the distribution of nanoparticles in abstracts of publications in the full nano S&T domain, we see that C60, silver nanoparticles, and zinc oxide are more likely to be found in the 2007 nano EHS data set than in the larger nano S&T publications, while carbon nanotubes are equally likely to be in both data sets (See Fig. 2).

By country of author affiliation, the US has the largest number of nano EHS publications in 2007, followed by Germany, China, UK, Japan, and South Korea (see Table II). Compared to their total publication outputs in all nano domains, the US, Western European countries, and Australia have a relatively greater emphasis or specialization on nano EHS while China and Japan are less specialized. In addition to differences in systematic national policy attention to EHS, an explanatory factor is that the US and other more specialized countries do more nanoscale research in fields that are prominent in EHS work such as biomedical science and environmental disciplines, whereas Chinese research tends to be concentrated in more broad-based materials and chemistry disciplines. For example, US nano S&T publication concentrations are represented by specialization figures above 1.00 (where 1.00 means the country is more specialized in a “macro-discipline” than the overall database, see description of “macro-discipline” below) in areas such as Biomedical Science (1.55), Clinical Medicine (1.46), Infectious Diseases (1.44), Geosciences (1.57), Ecological Sciences (1.37), Environmental Science and Technology (1.07) but lower specialization figures in Materials Science (.91) and Chemistry (.93). In comparison, China’s nano S&T publication concentrations are represented by specialization figures above 1.00 in Materials Science (1.05) and Chemistry (1.16) but lower specialization figures in Biomedical Science (.49), Clinical Medicine (.52), Infectious Diseases (.25), Geosciences (.39), Ecological Science (.38), and Chemistry (.38) the most highly specialized of all the nano disciplines (see Table II).
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Table II. Nano EHS publications by leading countries, 2007.

<table>
<thead>
<tr>
<th>Country</th>
<th>EHS</th>
<th>Total (×1000)</th>
<th>EHS % of total</th>
<th>Index of specialization*</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>80</td>
<td>14.9</td>
<td>0.54</td>
<td>1.12</td>
</tr>
<tr>
<td>Germany</td>
<td>35</td>
<td>5.6</td>
<td>0.63</td>
<td>1.32</td>
</tr>
<tr>
<td>China</td>
<td>28</td>
<td>12.0</td>
<td>0.23</td>
<td>0.49</td>
</tr>
<tr>
<td>UK</td>
<td>21</td>
<td>3.3</td>
<td>0.63</td>
<td>1.31</td>
</tr>
<tr>
<td>Japan</td>
<td>20</td>
<td>6.1</td>
<td>0.33</td>
<td>0.69</td>
</tr>
<tr>
<td>South Korea</td>
<td>20</td>
<td>3.2</td>
<td>0.62</td>
<td>1.30</td>
</tr>
<tr>
<td>France</td>
<td>15</td>
<td>3.5</td>
<td>0.43</td>
<td>0.89</td>
</tr>
<tr>
<td>Italy</td>
<td>13</td>
<td>2.4</td>
<td>0.55</td>
<td>1.15</td>
</tr>
<tr>
<td>Australia</td>
<td>11</td>
<td>1.2</td>
<td>0.94</td>
<td>1.95</td>
</tr>
<tr>
<td>India</td>
<td>10</td>
<td>2.7</td>
<td>0.37</td>
<td>0.77</td>
</tr>
</tbody>
</table>

*The specialization index is the ratio of nano EHS to all nano S&T publications for a given country divided by the same ratio for the whole nano S&T publication database in 2007. More specialized in nano EHS > 1.00; Less specialized in nano EHS < 1.00.

Table III. Nano publications by journal subject categories, ranked by citations to nano EHS publications, 2006 v. 2008.

<table>
<thead>
<tr>
<th>Cited journal subject category</th>
<th>2006</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Materials Science, Multi.</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2. Chemistry Physical</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3. Physics Applied</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4. Physics Condensed Matter</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>5. Multidisciplinary Sciences</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>6. Chemistry Multidisciplinary</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>7. Physics Multidisciplinary</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>8. Physics, Atom. Mole. Chem.</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>9. Nanoscience and Nanotech.</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>33. Environmental Sciences</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>39. Engineering, Environment</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>68. Public, Envi, Occup. Hlth.</td>
<td>75</td>
<td>75</td>
</tr>
</tbody>
</table>

Table IV. Top nano EHS journal subject categories, 2004 and 2007.

<table>
<thead>
<tr>
<th>Journal subject category</th>
<th>2004</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Chemistry, Multidisciplinary</td>
<td>1</td>
<td>Toxicology</td>
</tr>
<tr>
<td>2. Pharmacology and Pharmacy</td>
<td>2</td>
<td>Materials Science, Multi.</td>
</tr>
<tr>
<td>3. Materials Science, Multi.</td>
<td>3</td>
<td>Pharmacology and Pharmacy</td>
</tr>
<tr>
<td>4. Environmental Sciences</td>
<td>4</td>
<td>Chemistry, Multidisciplinary</td>
</tr>
<tr>
<td>5. Biochemistry and Molecular Biology</td>
<td>5</td>
<td>Environmental Sciences</td>
</tr>
<tr>
<td>6. Cell Biology</td>
<td>6</td>
<td>Biochemistry and Molecular Biology</td>
</tr>
<tr>
<td>7. Toxicology</td>
<td>7</td>
<td>Nanoscience and Nanotechnology</td>
</tr>
<tr>
<td>8. Physics, Applied</td>
<td>8</td>
<td>Physics, Applied</td>
</tr>
</tbody>
</table>
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Fig. 3. Macro-Disciplines of Nano EHS Publications, 2004 and 2007.

the use of nanotechnology for ecological forecasting and detection of ecological toxicity from nanomaterials. We also examine the degree of “integration” of multiple disciplines in nano EHS by calculating an “integration score” from a similarity matrix of cited SCs for a threshold of papers with at least four cited references and at least three cited SCs. The integration score ranges from zero (i.e., a stand-alone discipline that cites no work from outside its discipline) to one (i.e., a highly integrated work that cites largely from diverse disciplines). The mean integration score for nano EHS is 0.54 (standard deviation = .12). This figure suggests moderate levels of multidisciplinarity in nano EHS.

Given the Royal Commission Report’s recommendation about the importance of bridging biotoxicity and ecotoxicity research in nano EHS, it is appropriate to examine the specific link between these two fields. In particular, we examine the extent to which environmental nano EHS publications cite biomedical works and the extent to which biomedical nano EHS publications cite environmental works. Nano EHS publications with SC names that incorporate “envir-” or “ecology” are considered environmental nano EHS; publications with SC names that incorporate “bio” or “health” are considered biomedical nano EHS for the purpose of this analysis. The results from our 2007 nano EHS database show that environmental nano EHS publications are more apt to cite biomedical nano EHS works than the reverse. Less than one-fourth of the 53 biomedical nano EHS publications in 2007 cite environmental nano EHS works, whereas more than half of the 29 environmental nano EHS articles in 2007 cite biomedical works. This is an early examination of multidisciplinary cross-citation to be sure but it does suggest that the disciplinary gap is more prevalent on the biomedical side than the environmental side.

Fig. 4. Map of Science: Subject Categories of Risk within Nano, 2007.

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4. CONCLUSIONS

This paper has examined the growth and diffusion of nano EHS research using bibliometric analysis of WOS SCI publications in the Georgia Tech global nanotechnology database. We were guided by two research questions: (1) to what extent has nano EHS publication activity developed alongside that of the broader nano S&T domain, and (2) how have nano EHS publications diffused across specific disciplinary boundaries. The importance of these research questions lies in the understanding the extent to which attention to EHS issues is occurring concurrently with, and in relationship to, the development of broader nano R&D (and not afterwards). The simultaneous development of EHS and nano S&T work is highlighted by policymakers and others to avoid problems that have affected some previous technologies as well as to ensure that nano-related risks are avoided or minimized.

The results of our research show that nano EHS publications are small in scale relative to the broader nano S&T area, though growing very rapidly. This growth rate suggests that there is the potential for nano EHS work to broaden its impact on nanotechnology S&T research. However, the diffusion of nano EHS work will face challenges, notably the challenge of scale—i.e., the magnitude of the general nano S&T body of work compared to the smaller size of nano EHS work. However, one could also argue that the bigger that the broader nano S&T gets, the greater opportunities for EHS growth and interconnection. This difference in size of the two domains will likely persist, notwithstanding (at least in the US) the increase in public funding for nano EHS research in recent years. In addition to funding expansions, there may need to be a much greater emphasis over the next few years on the communication and impact of nano EHS work if the goals of nanotechnology governance for simultaneous attention to nano S&T advances and nano EHS affects are to be addressed.

The diffusion of nano EHS work across disciplinary boundaries within the nano domain is of particular importance to the development and application of specific areas of nanoscience and nanotechnology. The report by the Royal Commission on Environmental Pollution states that there is a need for linkages between biomedical and environmental cooperation in nano EHS to “enhance the development of robust test systems and also to act as a catalyst for early warnings from observations on lower organisms to be extrapolated to humans.” Our analysis showed that the nano EHS area as a whole is somewhat multidisciplinary, with a strong presence of materials science, chemistry, biomedical science, and environmental science and technology, though some gaps show in the agricultural and ecological sciences. When focusing on the sharing of knowledge, as measured by cited references, across the biomedical and environmental nano EHS areas, our findings indicate that there is more bridging from the perspective of environmental nano EHS citation of biomedical references than in the reverse direction. The ability to make environmental nano EHS research available and useful to biomedical nano EHS research is a noteworthy area of future attention. Continued monitoring of the relationships of nano EHS between disciplinary boundaries, as well as across the broader nano field, will be helpful to the ongoing development of nano R&D.

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