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Nanotechnologies and Green Knowledge Creation: Paradox or Enhancer of Sustainable Solutions?

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Abstract By exploring whether nanotechnologies have the potential to generate green innovations, we consider the paradox between the negative and positive side-effects that could come with the development of nanotechnologies. Starting from the conceptual framework of green product innovation, the potential green innovation activity of more than 14,000 firms of the nanotech sector is investigated. Using a query-search method, their patenting activity is explored. Results first show that there is an increasing trend toward the creation of fundamental green knowledge by firms involved in nanotechnologies; second, they demonstrate that energy efficiency is the main driver of green knowledge creation in the sector and third they reveal the main characteristics of nanotech firms creating green knowledge. Beyond their contribution to the debate between positive and negative outcomes of nanotechnology developments, these results also enrich the conceptual framework of green product innovation—a key route to achieving sustainability at the same time as growth.

Keywords Innovation · Sustainability · Nanotechnology · Knowledge creation · Patents

Introduction

Sustainability has become a mainstream concern for businesses and governments as well as in the general public arena. While the goal of organizations' activities remains economic performance, this now includes the reduction of their negative side-effects on the natural environment and on society.

Nanotechnology, which appears to be one of the most promising technologies today, may have the potential to address major global sustainability problems, e.g., facilitating the decrease of pollution caused by insecticides or access to more energy efficiency. Much uncertainty and anxiety exist about the nanotechnologies' potential side-effects—that it may introduce new undesirable environmental, health, safety, and social factors—and many commentators are making analogies with the dangers of nuclear power, asbestos, and Genetically Modified Organisms. There, therefore, seems to be a paradox in respect to the development of nanotechnologies and the quest for more sustainability.

This paradox is the starting point for our study. By exploring if and how nanotechnologies have the potential to generate green product innovation, we give more thought to this paradox. Our research participates in the debate developed within society between those who defend nanotechnologies by citing their potential positive outcomes and those who warn of the potential negative side-effects. For example, because they provide more efficient materials, nanotechnologies can increase energy efficiency through cheaper solar power and contribute to more efficient and cleaner production processes, improve water filter systems and environmental sensing and modeling. In the health sector, they provide nanoporous membranes for more accurate, small and stable disease diagnosis and drug delivery. However, nanoparticles have the ability to slip past the human system unnoticed or disperse into the environment with still badly known consequences, leading to the emergence of ownership and responsibility issues. Moreover, they may be used to alter privacy conditions (Wood et al. 2008).

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Some suggest that companies should modify the way they innovate in nanotechnology so as to meet wider societal goals (Groves et al. 2011), e.g., arguing that green innovation may increase a firm's competitiveness (Chen et al. 2006). Beyond some theoretical contribution on green product innovation, this research may also have an impact on decisions of policy makers and investors in the nanotechnology sector.

To explore if nanotechnologies have the potential to generate green product innovation, our research analyzes green knowledge creation of firms which patent in nanotechnology. A database of more than 600,000 nanotechnology patent applications over the last 10 years has been built and analyzed in this article. A query to track the sustainability dimensions of these patents is established, and an analysis of the characteristics of firms creating green knowledge in nanotechnologies is given by age, size, industry, and localization.

This article is structured as follows: we first review literature and precise research questions to address the gap, we then describe the methodology, present and discuss results and finally offer our conclusion.

Literature Review and Research Questions

Sustainability has become a mainstream concern and the concept of 'sustainable development' has reached the public arena at a global level (Barkemeyer et al. 2009). According to the last (2010) UN Global Compact-Accenture survey—the most extensive survey of CEOs' views on sustainability—"For many consumers, sustainability is no longer just 'nice to have' but is instead a critical differentiator." In the last few decades, governments and businesses have begun to adopt more sustainability dimensions into their policies and economic activities, while an increasing number of companies rely on sustainability indicators to assess their level of corporate social responsibility (CSR) (Callado and Fensterseifer 2011). Some commentators claim that there is no alternative to the adoption of such practices (Nidumolu et al. 2009), while others even argue that not considering sustainability issues would be unethical (Tang 2010). Although the goal of organizations' activities remains economic performance, this now includes the reduction of their negative side-effects on the natural environment and on society (Bansal 2002). Academic research has provided many theoretical developments, as well as empirical evidence from the field supporting sustainability (Shrivastava 1995; Gladwin et al. 1995; Dyllick and Hockerts 2002; Hahn and Scheermesser 2006; Hahn et al. 2010), and this new awareness has made marketing green products a necessity for many companies (Simon 1992).

Green products strive to protect or enhance the natural environment by conserving energy and/or resources and reducing or eliminating the use of toxic agents, pollution, and wastes (Ottman et al. 2006). Greenbiz (2009) reports that more than 1,500 new products dedicated to such ends were launched in the US in that year. Scholars' interest in such products has been growing (Roy et al. 1996; Chen 2001; Chung and Tsai 2007; Pujari et al. 2003; Rehfeld et al. 2007) and Roy et al. (1996) have proposed a conceptual framework for green product innovation.

Green product innovation has been recognized as "one of the key factors to achieve sustainable growth, environmental sustainability and a better quality of life" (Dangelico and Pujari 2010, p. 471), resulting from a systemic process with three main environmental foci: materials, energy, and pollution (Dangelico and Pujari 2010). This process relies on a life-cycle assessment which ensures the control of environmental impacts at each stage of the product's physical life-cycle (Gauthier 2005; Linton et al. 2007), and requires enhanced levels of corporate environmental responsibility. Green product innovation can bring the developing firm substantial levels of both product differentiation and competitiveness, as well as greater societal legitimacy (Bansal and Roth, 2000; Gonzalez-Benito and Gonzalez-Benito 2006). This conceptual framework proposes innovative solutions including reduction/recycling of materials/product/packaging, use of renewable or biodegradable materials, prevention/decrease of pollution and energy efficiency (see Fig. 1), but does not describe how knowledge enhancing green innovation—such as new ideas at the beginning of the value chain—can be created.

It is widely recognized in the innovation literature that firms mobilize both fundamental and applied knowledge in their productive activities (Nelson 1959)—that is knowledge, in conjunction with resources, which gives them their capacity to act. Kaplan et al. (2001) identifies six critical capabilities: creation, destruction, integration, absorption, replication, and protection. Kogut and Zander (1992) consider a firm's competitive advantage stems from its skills in knowledge creation and transformation, while Cohen and Levinthal (1990) suggest that knowledge creation and accumulation bring increasing returns, and Hill and Rothaermel (2003) find that knowledge creation allows firms to increase their absorptive capacity, i.e., their ability to "recognize the value of new information, assimilate it, and apply it to commercial ends" (Cohen and Levinthal 1990). Building the relevant absorptive capacity of the firm provides companies with options to expand into new markets in the future (Kogut and Zander 1992) and the ability to cope with technological change (Cohen and Levinthal 1990). Altogether, the capability to create new knowledge is considered as one the main sources of the firm's competitive advantage (Nonaka 1991; Teece 1998).

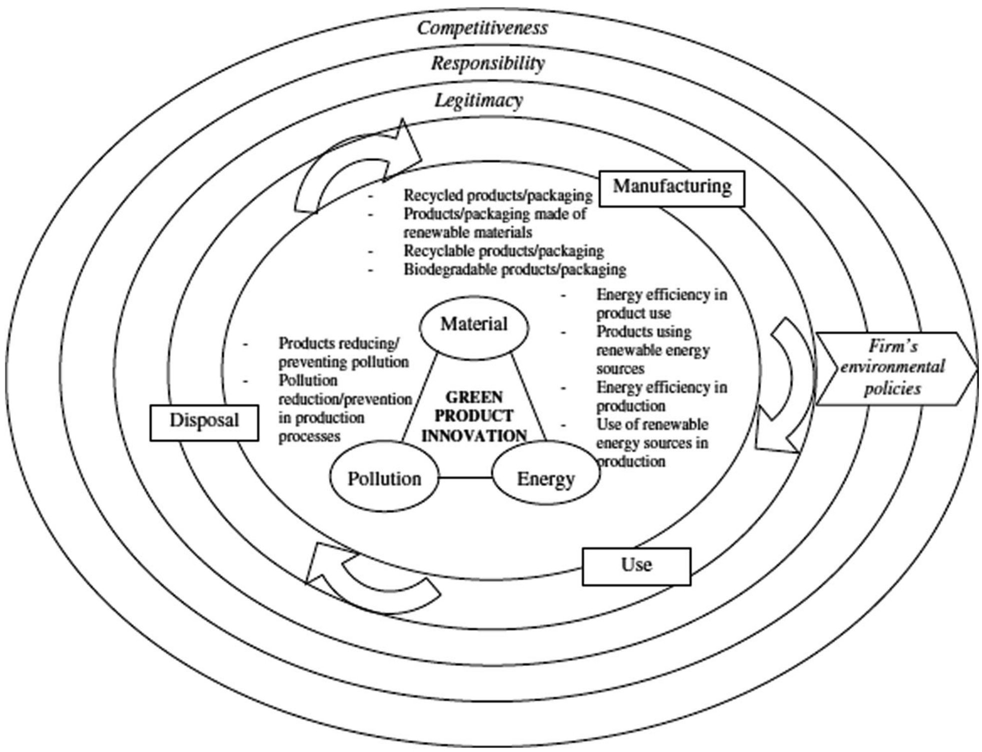

Fig. 1 A conceptual framework for green product innovation (from Dangelico and Pujari 2010)

Chen et al. (2006) study the influence of green innovation on corporate advantage, looking at green innovation through product and process innovation, and showing how green product innovation can increase a firm's competiveness. Chung and Tsai (2007) study the relationship between green design activities (which minimize the impact of product and manufacturing processes on health, quality, and security through systematically considering these issues) and new product strategies: but while they establish positive correlations between green design activities and new product strategies on the one hand, and product performance on the other, they do not explain how green knowledge is developed. Chen (2008a), exploring the role of intellectual capital for green innovation, proposes a novel construct—'green intellectual capital'—which has three categories: green human capital, green structural capital and green relational capital, and shows positive effects on firms' competitive advantages. Chen (2008b) also explores the influence of the firm's core green competences on its green innovation performance and green image. However, none of these studies address the question of knowledge creation—which therefore remains something of a 'black-box,' whose exploration is a significant issue if further sustainable solutions are to be found. Given that "green product innovations are characterized as radical if they are new to the market, but also if they are based on a radically new technology, and/or have been patented by the firm" (Dangelico and Pujari 2010, p. 477), it would be logical to introduce fundamental knowledge creation into the green product innovation framework. This article therefore addresses the question of the characteristics and determinants of green fundamental knowledge creation.

To explore the question of fundamental green knowledge creation, we investigate the knowledge base of what is currently the world's most promising emergent technology—nanotechnology. Romig et al. (2007) define the term as referring to R&D developments at the atomic, molecular, or macromolecular levels (i.e., in the range of approximately 1–100 nm in length); the creation and use of structures, devices and systems that have novel properties and functions because of their small and/or intermediate size; and the ability to control or manipulate material at the atomic or nanometric scales. Nanotechnology is expected to bring about the next major technological, industrial (and thus economic) revolution (Roco and Bainbridge 2005; Peterson 2004)—Wonglimpiyarat (2005) and Kautt et al. (2007) refer to this prospect as a 'nano-revolution,' and even suggest that "micro and nano technology is the harbinger of the next Schumpeterian or Kondratieff wave" (Schumpeter 1939, 1967; Kondratieff 1978).

By taking advantage of new opportunities and proposing new applications to answer the world's main health, agricultural and environmental challenges, nanotechnology may have the potential to address major global sustainability problems (Kalpana Sastry et al. 2010; Joshi 2008), including "…improving people's standard of living, healthcare and nutrition; reducing or even eliminating pollution through clean production technologies; repairing existing environmental damage; feeding the world's hungry; enabling the blind to see and the deaf to hear; eradicating diseases and offering protection against harmful bacteria and viruses; and even extending the length and the quality of life through the repair or replacement of failing organs" (SwissRe 2004, p. 7).

There is therefore a paradox in respect to the potential positive outcomes of the development of nanotechnologies and their possible negative consequences. A recent comprehensive literature review (Kleijnen et al. 2009) identifies a total of seven driving factors of resistance to innovation which can be applied to nanotechnology. They are divided into four elements of risk—physical, economic, functional, and social—and three other factors which are threats to traditions and norms, insecurity about usage patterns, and the perceived image of the technology. Numerous stakeholders—investors, insurers, unions, scientists, civil society, NGOs, and the media—are already questioning the potential negative effects of nanotechnology and calling for precautionary or even regulatory measures. A study conducted by Nakagawa et al. (2010) specifies the heterogeneous perceptions about its negative and positive effects among a sample of stakeholders. The importance of abiding by the precautionary principle is seen as being particularly relevant for nano-innovations because of the very considerable scope, weight, and nature of their potential consequences (Throne-Holst and Stø 2008). Groves et al. (2011) propose that companies should address these stakeholders' concerns by modifying the way they innovate in nanotechnology in order to meet wider societal goals, while a short guide by McDinn (2010) seeks to raise the awareness of nanotechnology researchers about their ethical responsibilities, "…researchers must remember that the legitimate interests of the ever-present 'background client,' i.e., society at large, are paramount" (p. 12).

Exploring the green innovation potential of nanotechnology firms' knowledge portfolios can allow us to determine whether this promising new technology can indeed contribute to global sustainability. Sustainable or environmental technologies are defined as those which are (or are potentially) available that could contribute to helping decrease human pressures on the environment or natural resources while at the same time maintaining desired standards of living (Kraines and Wallace 2003). R&D data offer a straightforward measure of innovative activity and, in particular, patent data (unlike more aggregate data such as R&D expenditures) can provide a detailed record of every invention (Griliches 1990). Patents represent the origins and features of a new technology (Choi et al. 2007), and are the most commonly used indicator of technology change in literature (Sun et al. 2008). Studying patent applications—rather than only patents awarded—allows us to understand both existing and forthcoming trends in innovation. This article examines nanotechnology patent applications in order to study the creation of green knowledge by companies.

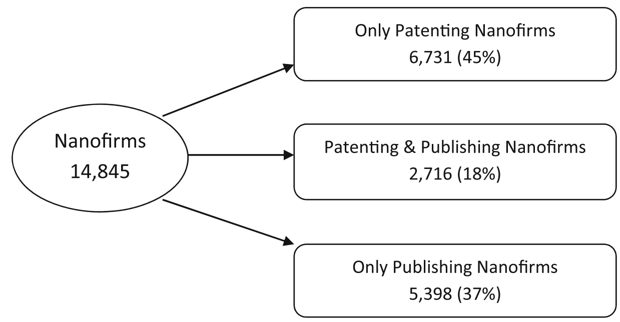

Fig. 2 Extraction of nanofirms which patent and which publish

We can then define the precise research questions this article addresses in order to solve the paradox in respect to the potential negative side-effects that nanotechnologies can introduce and their ability to address major sustainability:

(1) Do firms involved in nanotechnologies create green knowledge, i.e., do nanotechnology patent applications contain dimensions for sustainability?
(2) What is the main driver (energy efficiency? pollution decrease? reduction of water consumption?) of green knowledge creation in the nanotech sector?
(3) What are the main characteristics (age, size, industry, location) of firms which create green knowledge?

Methodology

To identify those firms involved in nanotechnology, we built a database of firms that have patented or published in nanotechnology, using a validated search strategy based on keywords (Mougotov and Kahane 2007) to extract patents from the EPO PatStat at the European Patent Office[1] (which collects data from 73 offices worldwide) and publications from the ISI/web of Science. We elicited 617,000 nanotechnology patent applications (from a total of over 65,000,000) between 1990 and 2009 (see Appendix 1 for details). We thus identified 14,845 firms involved in nanotechnology worldwide, of which 9,447 were patenting firms (2,716 both publishing and patenting; 6,731 only patenting) (Fig. 2), responsible between them for 323,918 nanotechnology patent applications over that period.

To uncover economic and financial information about the nanofirms that create green knowledge, we then matched this database against ORBIS,[2] a comprehensive global database that combines information on some 60 million

[1] See www.epo.org

[2] See www.bvdinfo.com

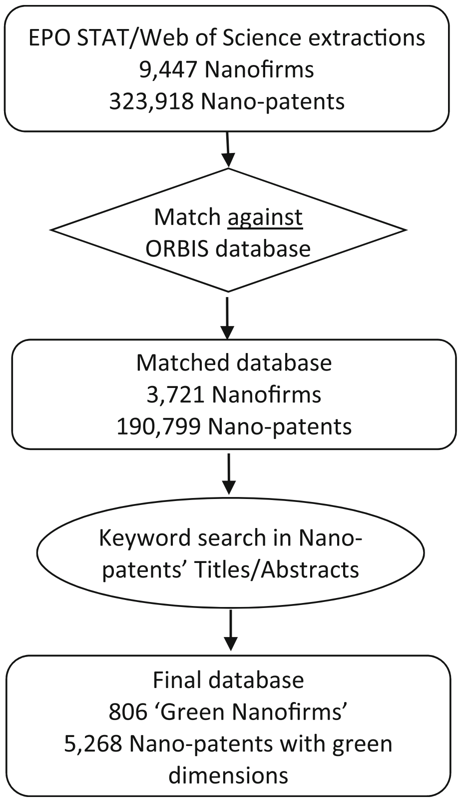

Fig. 3 Data acquisition processes

companies, from nearly 100 sources, and which gives comparable financial information across public and private companies, filtered into various standard report formats. By crossing the ORBIS and the EPO PatStat data (see Fig. 3), we were able to identify 3,721 'nanofirms' who were responsible for 190,799 nanopatent applications, and about which we could gather full data. (The study ends in 2007 in order to consider only those years with complete data.)

To identify the green patenting activity of nanotechnology firms, we checked patent titles and abstracts to track environmental dimensions through their patent applications, using a formal 'nominalist' search tracking strings of keywords corresponding to the Global Reporting Initiative's (GRI)[3] environmental indicators of the group or firm. The GRI is a multiple stakeholder organization that has pioneered the most widely used framework for sustainability reporting, and a recent analysis shows its indicators offer a good basis for comparing firms' sustainability performance (van den Brink and van den Woerd 2004). Beyond the usual economic performance indicators, the GRI lists indicators of environmental performance (materials/energy/water/biodiversity/emissions, effluents, and waste/transport) and of social performance. Given our focus on green innovation, we retained only the environmental performance indicators in our analysis, and double-checked them using the work of Popp (2005), and then regrouped them around the three dimensions proposed in our conceptual green product innovation framework—materials, energy, and pollution. The data search query was first applied to all environmental indicators together, and then to each indicator individually, to identify research priorities in the green innovation field (queries are given in the Appendix.) This whole acquisition process (see Fig. 3) allowed us to identify a final group of 806 'green nanofirms'—i.e., nanofirms with at least one nanopatent incorporating environmental dimensions in their knowledge portfolios.

[3] See www.globalreporting.org

Results and Discussion

Increasing Trend of Green Knowledge Creation

Concerning the characteristics of fundamental green knowledge creation, our data reveal that 806 nanofirms—more than 22 % of our matched database—create green knowledge (see Table 1), having at least one patent with environmental dimensions in their portfolio. More than half of them (56 %) also publish, indicating that they are active in basic as well as applied research, which implies that green issues are taken into account at the earlier stages of product innovation, i.e., that green product innovation comes from knowledge creation, which was not explicit in the previous conceptual innovation framework (Roy et al. 1996; Dangelico and Pujari 2010). Nanopatent applications that integrate environmental dimensions account for 5,268 (3.63 %) of the 144,781 patent applications filed by our 806 nanofirms (see Table 1). Green knowledge creation in the nanotechnology field occurs in firms that are not dedicated to sustainability, meaning that green innovation happens in a context of knowledge base hybridization (Hill and Rothaermel 2003), where firms' knowledge bases are built from recombining parts of their established knowledge bases with this new stream of knowledge (Freeman and Soete 1997).

From a dynamic perspective, we can observe that the trend of patent applications to include environmental dimensions has developed over time (Fig. 4), showing the growing interest of firms which create green knowledge.

Table 1 Descriptive statistics of green knowledge creation in nanotechnology firms

	Firms		Nanopatents		Green nanopatents	
Green Nanofirms	806	22 %	144,781	76.88 %	5,268	3.63 %
Total	3,721	100 %	190,799	100 %	144,781	100 %

There is an apparent combination between nanotechnologies and green knowledge creation.

Energy Efficiency is the Main Driver of Green Knowledge Creation

Figure 5 shows that the dimension most often investigated in green knowledge creation is that of energy, followed by pollution and materials.

Bansal and Roth (2000) have identified three main motivations that drive firms to embrace sustainability—competitiveness, compliance with regulations and a sense of ecological responsibility—and we find this echoed in our results. Energy efficiency is the main driver of green innovation in the nanotechnology sector and, in the current climate of rising energy costs and increasing awareness about climate change issues (UN Global Compact-Accenture 2010), energy efficiency remains a key issue for a firm's competitiveness. As the market's demand for energy efficiency increases, innovation in the energy field reduces firms' production and transportation costs. Awareness of pollution seems also to be a driver of green innovation, and the need to comply with regulations (e.g., Clean Air Act in the US, Kyoto Protocol) may also explain the R&D strategies adopted by many firms about such issues. We can see how green knowledge creation clearly complements the creation of virtuous circles based on the life-cycle analysis that is part of a conceptual green product innovation framework,

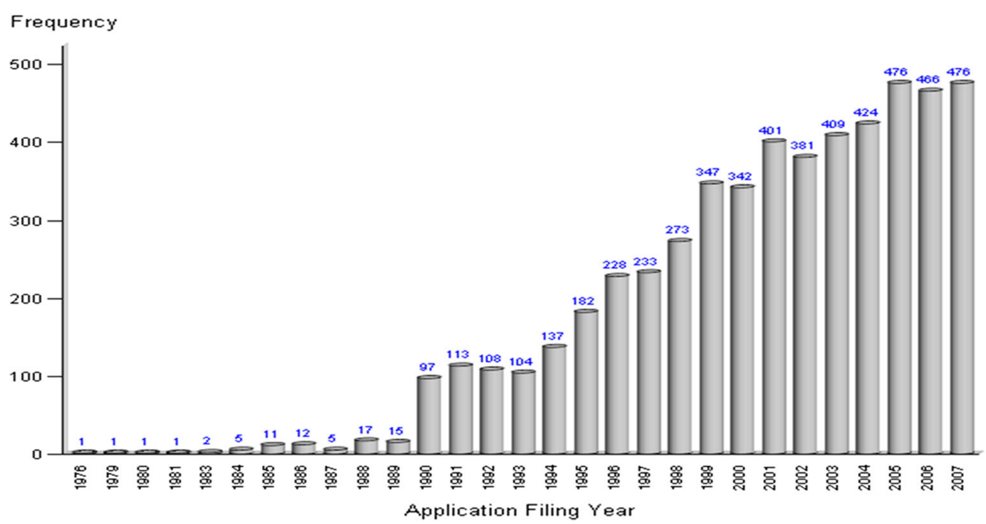

Fig. 4 Trend in Nanofirms' applications for green patents until 2007

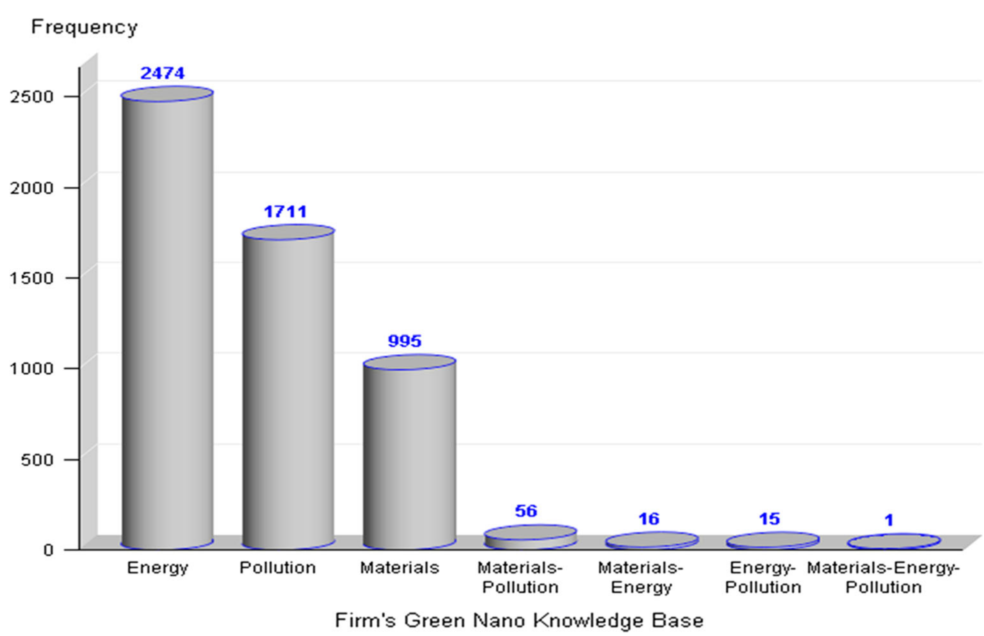

Fig. 5 Dimensions of green knowledge creation

thereby enhancing its efficiency. The data search queries proposed in this research can also highlight environmental factors that are considered in the development of other technologies, and our methodology could be reproduced in other contexts, such as considering environmental effects as a part of technology evaluation (Hung and Tseng 2010).

Characteristics of Firms Which Create Green Knowledge Research Hypotheses

In terms of what determines green knowledge creation in nanotechnology firms, available data reveal that 85.83 % of green nanofirms and 91 % of green knowledge were created before the 'nano-wave period' (i.e., pre-2000), when key nanotechnology research opportunities became clearer (Roco et al. 2000). We also observe that the nanofirms which create green knowledge are mainly older companies (Table 2). We then propose:

Hypothesis 1 Green knowledge creation in the nanotechnology field is positively associated with the firm's age.

Nanofirms involved in green patent applications are also mainly very large companies (Table 3). More than half are very large firms in terms of the ORBIS size categories (i.e., with operating revenues of at least US $140 m or over 1,000 employees) and are responsible for the creation of more than 75 % of green knowledge.

This impression—that sustainability seems of more concern to very large nanotechnology firms rather than large or SMEs—aligns with Bansal's (2005) suggestion of a positive link between organizational size and corporate sustainable development. His focus on sustainability appears to offer incumbents both the impetus and the opportunity to innovate, and we echo Rosenbloom (2000) and Cattani (2006) in finding that, in radical innovation contexts, those large incumbent firms that can adapt and survive disruptive change are often responsible for numerous innovations, enriching their knowledge bases by recombining parts of their established knowledge base with new knowledge streams (Hill and Rothaermel 2003). By definition—since they are already large and established—such firms will not be nanotechnology based: it would therefore appear that green knowledge creation in the nanotechnology field occurs mainly in firms that are not themselves dedicated to nanotechnology (Mangematin et al. 2011). We therefore have:

Hypothesis 2 Green knowledge creation in the nanotechnology field occurs mainly in very large firms.

We used the North American Industry Classification System (NAICS) to determine the focal industries of our population of nanofirms, and found that those creating green knowledge operate mainly in manufacturing industries (Computer and electronic products, Chemicals, Machinery, Metal/Non-Metal fabrication, Miscellaneous, Transportation and Electrical equipment manufacturing, etc.) which account for more than half (536 of the 806 green nanofirms) and for 4,252 green nanopatents (81 %) (Table 4): the fact that manufacturing activities have traditionally been the most polluting may explain this trend. Green patenting activity is highest in the Computer and electronic product manufacturing sector (31.91 %), followed by the Chemical manufacturing sector (19.74 %) and then the service sector (where such activity focuses on instrumentation) (8.36 %). However, green knowledge creation in the nanotechnology field remains dispersed across different industries. We suggest:

Hypothesis 3 The Computer and electronic product manufacturing sector has more impact on green knowledge creation in the nanotechnology field than in the other sectors.

In terms of firms' geographic locations, it appears that more than 70 % of green nanofirms are located in Europe and US/Canada, however, the Asian firms are more involved in creating green knowledge with a share of almost 50 % (Table 5). This finding has a particular interest, in that such data are relatively rare among existing studies: most research studies about firms and sustainability have explored companies in the western hemisphere, but our study avoids that bias by exploring worldwide patent applications. This relatively greater activity by Asian firms is likely to impact on the

Table 2 Green knowledge creation in nanotechnology firms by year of incorporation

Incorporation year	Green nanofirms		Green nanopatents	
Pre-1950	242	30.02 %	2,383	45.24 %
1951–1990	264	32.75 %	1,731	32.86 %
1991–2007	300	37.23 %	1,154	21.90 %
Total	806	100 %	5,268	100 %

Table 3 Green knowledge creation in nanotechnology firms by size

Firm size	Green nanofirms		Green nanopatents	
Small	112	13.90 %	314	5.96 %
Medium	136	16.87 %	524	9.95 %
Large	111	13.77 %	397	7.54 %
Very large	447	55.46 %	4,033	76.55 %
Total	806	100 %	5,268	100 %

Table 4 Green knowledge creation in nanotechnology firms by sector

Industry (NAICS 2007)	Green nanofirms		Green nanopatents	
Computer and Electronic Product Manufacturing	119	14.76 %	1,675	31.91 %
Chemical Manufacturing	164	20.34 %	1,036	19.74 %
Professional, Scientific, and Technical Services	125	15.50 %	439	8.36 %
Machinery Manufacturing	58	7.19 %	349	6.65 %
Electrical Equipment, Appliance, and Component Manufacturing	29	3.59 %	307	5.84 %
Transportation Equipment Manufacturing	29	3.59 %	181	3.44 %
Merchant Wholesalers, Durable Goods	36	4.46 %	174	3.31 %
Primary Metal Manufacturing	29	3.59 %	157	2.99 %
Miscellaneous Manufacturing	30	3.72 %	143	2.72 %
Plastics and Rubber Products Manufacturing	13	1.61 %	121	2.30 %
Nonmetallic Mineral Product Manufacturing	23	2.85 %	94	1.79 %
Administrative and Support Services	18	2.23 %	60	1.14 %
Merchant Wholesalers, Nondurable Goods	18	2.23 %	58	1.10 %
Fabricated Metal Product Manufacturing	20	2.48 %	56	1.06 %
Printing and Related Support Activities	1	.12 %	43	.81 %
Oil and Gas Extraction	3	.37 %	41	.78 %
Telecommunications	7	.86 %	39	.74 %
Paper Manufacturing	6	.74 %	39	.74 %
Management of Companies and Enterprises	11	1.36 %	32	.60 %
Petroleum and Coal Products Manufacturing	4	.49 %	24	.45 %
Health and Personal Care Stores	2	.24 %	21	.40 %
Personal and Laundry Services	6	.74 %	18	.34 %
Utilities	6	.74 %	17	.32 %
Gasoline Stations	3	.37 %	14	.26 %
Food Manufacturing	3	.37 %	13	.24 %
Rental and Leasing Services	2	.24 %	10	.19 %
Mining (except Oil and Gas)	2	.24 %	10	.19 %
Data Processing, Hosting and Related Services	1	.12 %	8	.15 %
Construction of Buildings	4	.49 %	8	.15 %
Ambulatory Health Care Services	4	.49 %	7	.13 %
Textile Mills	3	.37 %	6	.11 %
Repair and Maintenance	3	.37 %	5	.09 %
Miscellaneous Store Retailers	2	.24 %	5	.09 %
Lessors of Nonfinancial Intangible Assets (except Copyrighted Works)	2	.24 %	5	.09 %
Educational Services	3	.37 %	5	.09 %
Wholesale Electronic Markets and Agents and Brokers	1	.12 %	4	.07 %
Wood Product Manufacturing	1	.12 %	3	.05 %
Support Activities for Mining	2	.24 %	3	.05 %
Clothing and Clothing Accessories Stores	2	.24 %	3	.05 %
Textile Product Mills	2	.24 %	2	.04 %
Religious, Grantmaking, Civic, Professional, and Similar Organizations	1	.12 %	2	.04 %
Real Estate	2	.24 %	2	.04 %
Publishing Industries (except Internet)	1	.12 %	2	.04 %
Arts, Entertainment, and Recreation	1	.12 %	2	.04 %
Apparel Manufacturing	1	.12 %	2	.04 %
Motor Vehicle and Parts Dealers	1	.12 %	1	.02 %
Heavy and Civil Engineering Construction	1	.12 %	1	.02 %
Beverage and Tobacco Product Manufacturing	1	.12 %	1	.02 %
Total	806	100 %	5,268	100 %

Table 5 Green knowledge creation in nanotechnology firms by location

Location	Green nanofirms		Green nanopatents	
EU27	269	33.37 %	931	17.67 %
US/Canada	306	37.97 %	1,714	32.54 %
Asia	195	24.19 %	2,528	47.99 %
Others	36	4.47 %	95	1.80 %
Total	806	100 %	5,268	100 %

"nano-game" and give them an advantage as the worldwide demand for more green products, then

Hypothesis 4 The Asian firms have the highest impact on the green knowledge creation in nanotechnology field.

Measurements

As explained in the "Methodology" section, our database contains 806 green nanofirms, i.e., nanofirms with at least one nanopatent incorporating environmental dimensions in their knowledge portfolios.

The endogenous variable green knowledge creation was measured by the number of green nanopatents registered by the focal firm over the whole period.

We defined four sets of exogenous variables in the following table:

The age of the firm	
DumAge2	Dummy variable equals to one if the year of incorporation of the focal firm is between 1951 and 1990, and zero otherwise
DumAge3	Dummy variable equals to one if the year of incorporation of the focal firm is before 1951 and zero otherwise
The size of the firm	
DumVerylarge	Dummy variable equals to one if the focal firm's size is very large and zero otherwise
The activity sector of the firm	
DumSector1	Dummy variable equals to one if the activity sector of the focal firm is Computer and electronic product manufacturing
DumSector2	Dummy variable equals to one if the activity sector of the focal firm is Chemical manufacturing
DumSector3	Dummy variable equals to one if the activity sector of the focal firm is Professional, scientific, and technical services
DumSector4	Dummy variable equals to one if the activity sector of the focal firm is Machinery manufacturing
DumSector5	Dummy variable equals to one if the activity sector of the focal firm is Electrical Equipment, Appliance, and component manufacturing
The location of the firm	
DumUscanada	Dummy variable equals to one if the focal firm is located in North America
DumEu	Dummy variable equals to one if the focal firm is located in Europe
DumOther	Dummy variable equals to one if the focal firm is not located in North America, Europe, or Asia

Results

To test the four hypotheses, we perform an OLS regression; which analyses the determinants of the nanofirms green knowledge creation; using the STATA software. Table 6 shows the results. First of all, the effects of the selected independent variables on green knowledge creation are statistically significant at 5 % level.

Concerning the variables describing the firm's age the firms whose year of incorporation is between 1991 and 2007 served as a reference level. We found that the firms created before 1951 and those created between 1951 and 1990 have a more positive impact on green knowledge creation than the youngest firms. Similarly, the firms created before 1951 have more impact on green knowledge creation than those created between 1951 and 1990. So, the older the firm is the higher the number of green nanopatents will be, as expected with the descriptive statistics in Table 2. Therefore, Hypothesis 1 is well supported.

We can also notice that very large firms have more positive impact on the green knowledge creation than the other firms which validates the Hypothesis 2.

Furthermore, the results reveal that the Computer and electronic product manufacturing sector has the highest positive impact on green nanopatents creation followed by the Chemical manufacturing sector and so on. As a reference level, we took the sector with the lowest number of green nanopatents (Beverage and Tobacco Product Manufacturing sector, Table 4). Once again, the regression results align with the descriptive statistics (Table 4) leading to the approval of the Hypothesis 3.

Finally, the geographic area plays a significant role in the green knowledge creation and the results show that whatever the location, these firms have less impact on green knowledge creation than the Asian firms. Consequently, the Hypothesis 4 is confirmed. On the other side comparing the impacts of North Americans firms, European firms and firms from the rest of the world provides the same weights given by the descriptive statistics in Table 5.

Addressing the paradox

These results contribute to the debate on the paradox in respect to the potential negative side-effects that come with the development of nanotechnologies and the quest for more sustainability. They show that there is increasing creation of green knowledge in firms involved in nanotechnologies (research question (1)). It appears that green knowledge creation is mainly driven by energy efficiency in the nanotech sector (research question (2)). Finally, the answer to the research question (3) reveals that the creation of green knowledge by firms in the nanotechnology field occurs rather more in older firms (Hypothesis 1), in very large incumbent firms with a hybridized knowledge base (Hypothesis 2), in the Computer and electronic product manufacturing industries (Hypothesis 3), and that Asian firms are more involved in this type of knowledge (Hypothesis 4).

It follows that public decision-makers appear to favor investments for green knowledge creation in very large incumbent firms that are not only dedicated to nanotechnology. Considering the result that 'the promise of nanotechnologies is based on their ability to redefine existing industries, through new combinations, merging microelectronics with biotechnology,

Table 6 Green knowledge creation in nanotechnology firms

Variable	Label	Parameter estimate	Standard error	*t* value	Pr > |*t*|
Intercept	Intercept	6.33	2.69	2.35	0.019
DumAge2	Year of incorporation between 1951 and 1990 Dummy	1.95	0.96	2.03	0.043
DumAge3	Year of incorporation before 1951 Dummy	2.16	0.80	2.70	0.007
DumVerylarge	Very large nanofirms Dummy	5.08	0.79	6.36	<0.001
DumSector1	Computer and electronic product manufacturing sector Dummy	14.07	1.47	9.56	<0.001
DumSector2	Chemical manufacturing sector Dummy	9.30	4.45	2.09	0.037
DumSector3	Professional, scientific, and technical services sector Dummy	5.41	2.98	2.02	0.043
DumSector4	Machinery manufacturing sector Dummy	4.83	2.67	2.01	0.044
DumSector5	Electrical equipment, Appliance and component manufacturing sector Dummy	3.51	1.43	2.45	0.015
DumUscanada	Nanofirms from US and Canada Dummy	−2.45	1.21	−2.03	0.043
DumEu	Nanofirms from Europe Dummy	−5.32	1.27	−4.17	<0.001
DumOther	Nanofirms from the rest of the world Dummy	−5.40	2.73	−1.98	0.048
Adj *R*-squared		0.1837			

with chemistry, etc.' (Mangematin et al. 2011), it is suggested to investors in various new technologies to consider nanotechnologies as an enhancer of sustainable solutions.

In line with previous results about the central role of very large firms in the "nano-game" (Mangematin et al. (ibid.), Genet et al. (2012), managers and decision-makers should encourage circulation of knowledge among very large firms and their subsidiaries in order to enhance green knowledge creation. Moreover, very large firms being a central actor in the model for technology transfer in nanotechnology (Genet et al. (ibid.)), public research should facilitate such activity for green knowledge creation in order to create greater green product innovation.

Conclusion

This article uses a different approach to nanotechnology from that often employed: rather than focusing on the potential negative side-effects of the technology, it considers nanotechnology as a solution for issues involving ethics and the environment. We suggest that the resistance to innovation that characterizes the stances of many stakeholders could be reduced if the nanotechnology industry made sustainability an official aim in its roadmap, and that some social alarm could be managed more effectively if communication about nanotechnology focused more on efforts to develop green products aimed at solving existing environmental problems. Communicating about such green applications, and clearly evaluating negative and positive outcomes, could be a new way to increase the social acceptability of nanotechnology and counter global perceptions about nanotechnology's negative side-effects—in other words, if nanotechnology became more dynamic in fulfilling some of its promises, and ventured into new (green!) pastures, it may encounter less public resistance.

This research enriches the conceptual framework for green product innovation developed by Dangelico and Pujari (2010) by emphasizing that this framework must take into account the characteristics and determinants of green knowledge creation. As nanotechnology applications are increasingly applied to a myriad of industry contexts, managers should be aware of the challenge of transforming this knowledge into green product innovation. Further research could explore the link between knowledge creation and improvements in firms' internal processes. Our results provide evidence that different types of green products—those that are energy-based or material-driven—may require different approaches for integrating environmental sustainability. Managers can benefit from this more systemic approach to green innovation by gaining a clearer vision of the key drivers of innovation in specific fields. We suggest an in-depth multi-case analysis to explore links between green knowledge creation, its hybridization with established knowledge and the commercialization of green products.

This study also highlights the main characteristics of nanotechnology firms which create green knowledge, and emphasizes the active role that public policy can play in stimulating innovation in green product markets. The completed framework will help policy makers design more targeted innovation policies, aiming to enhance basic and applied research in green knowledge, to improve green processes during production life-cycles and to stimulate the demand for green products via subsidies and rebates for emerging green markets and industries such as energy-efficiency solutions or recycling. In a context where regulation is still relatively low, we show that interest in sustainability is growing in the world of nanotechnology: increased regulation will tend to enhance that trend, establishing sustainability performance as a key innovation driver rather than a constraint. Our results indicate that regulators should be aware of the major role played by very large incumbent firms in this context. A final contribution is the query search-based methodology developed in this article, which could be reproduced to measure the relative efficacy of a range of different initiatives, such as environmental regulation, voluntary initiatives (e.g., ISO14000), information disclosure or market mechanisms (e.g., trading in emissions permits) so as to help shape corporate sustainability.

Some emerging trends are shown which further research should explore. First, Asia seems to occupy a growing place in the green innovation game, which could change the geographic location of competitive advantages. Second, hybridization of knowledge appears to be a condition for green innovation, so the diversification of the nano knowledge base could be investigated by mapping the links between the different technological fields that have generated new nanopatents. Research could also explore how sustainability could be involved in the entire product development process, from idea generation and R&D to manufacturing and marketing, including products, services and technologies, as well as in new business and organizational models.

This research has some methodological limitations. First, only patents are explored here, but publications are another relevant indicator of knowledge creation, and further study should take this indicator into account. Second, the creation of green knowledge has been investigated only at company level, and the knowledge bases of other actors involved—universities, hospitals, non-profit institutions, and NGOs—also need analyzing.

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Appendices

Appendix 1: Description of data sources for patent applications

See Fig. 6

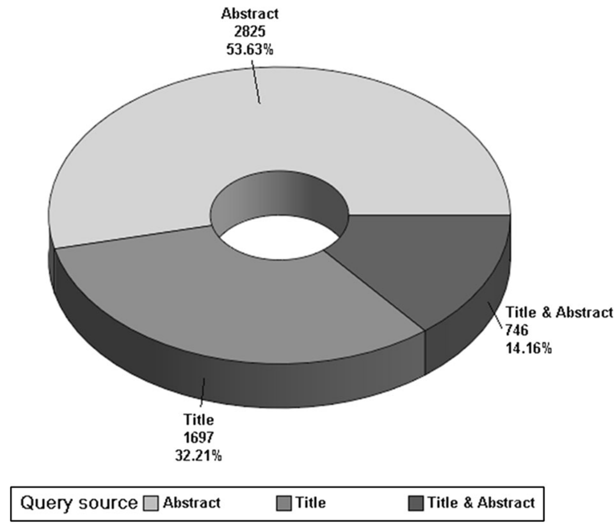

Fig. 6 Data sources for patent applications

Appendix 2: Query to identify priorities in green knowledge innovation: The 'Materials' dimension

```
*-------------------------------*/
/*-----Dim1 : -materials-----*/
/*------------------------------*/
appln_abstract  like '%materials%used%'
or appln_abstract  like '%materials%recycl%'
or appln_abstract  like '%recycl%materials%'
or appln_abstract  like '%materials%environment%'
or appln_abstract  like '%waste%plastic%'
or appln_abstract  like '%used%plastic%'
```

Appendix 3: Query to identify priorities in green knowledge innovation: The 'Energy' dimension

```
/*--------------------------------*/
/*-----Dim2 : -energy--------*/
/*-------------------------------*/

appln_abstract  like '%energy%consumption%'
or appln_abstract  like '%energy%efficiency%'
or appln_abstract  like '%energy%save%'
or appln_abstract  like '%energy%saving%'
or appln_abstract  like '%energy%renewable%'
or appln_abstract  like '%energy%reduction%'
or appln_abstract  like '%improved%energy%'
or appln_abstract  like '%solar%cell%'
or appln_abstract  like '%fuel%efficiency%'
or appln_abstract  like '%solar%energy%'
or appln_abstract  like '%dye%sensitized%'
```

Appendix 4: Query to identify priorities in green knowledge innovation: The 'Pollution' dimension

```
/*--------------------------------*/
/*-----Dim3 : -pollution------*/
/*--------------------------------*/

appln_abstract  like '%water%withdrawal%'
or appln_abstract  like '%water%recycl%'
or appln_abstract  like '%water%reused%'
or appln_abstract  like '%water%used%'
or appln_abstract  like '%recycl%%water'
or appln_abstract  like '%reused%%water'
or appln_abstract  like '%used%%water'
or appln_abstract  like '%water%discharge%'
or appln_abstract  like '%water%disposal%'
or appln_abstract  like '%water%transport%'
or appln_abstract  like '%water%import%'
or appln_abstract  like '%water%export%'
or appln_abstract  like '%water%treated%'
or appln_abstract  like '%water%habitat%'
or appln_abstract  like '%bio%diversity%'
or appln_abstract  like '%bio%diversity%protected%'
or appln_abstract  like '%bio%diversity%restored%'
or appln_abstract  like '%bio%diversity%conservation%'
or appln_abstract  like '%greenhouse%'
or appln_abstract  like '%green%house%'
or appln_abstract  like '%greenhouse%gas%'
or appln_abstract  like '%green%house%gas%'
or appln_abstract  like '%emission%reduction%'
or appln_abstract  like '% ozone %'
or appln_abstract  like '% no x %'
or appln_abstract  like '% nox %'
or appln_abstract  like '%nitrogen dioxide%'
or appln_abstract  like '% so2 %'
or appln_abstract  like '% so 2 %'
or appln_abstract  like '%sulfur dioxide%'
or appln_abstract  like '%pollution%'
or appln_abstract  like '%combatting%pollution%'
or appln_abstract  like '%bio%degradab%'
or appln_abstract  like '%bio%adhesive%'
```

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