RSC Advances

PAPER

Cite this: *RSC Adv.*, 2022, **12**, 11021

# The risk perception of nanotechnology: evidence from twitter

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Nanotechnology governance, particularly in relation to human and environmental concerns, remains a contested domain. In recent years, the creation of both a risk governance framework and council has been actively pursued. Part of the function of a governance framework is the communication to external stakeholders. Existing descriptions on the public perceptions of nanotechnology are generally positive with the attendant economic and societal benefits being forefront in that thinking. Debates on nanomaterials' risk tend to be dominated by expert groupings while the general public is largely unaware of the potential hazards. Communicating *via* social media has become an integral part of everyday life facilitating public connectedness around specific topics that was not feasible in the pre-digital age. When civilian passive stakeholders become active their frustration can quickly coalesce into a campaign of resistance, and once an issue starts to develop into a campaign it is difficult to ease the momentum. Simmering discussions with moderate local attention can gain international exposure resulting in pressure and it can, in some cases, quickly precipitate legislative action and/or economic consequences. This paper highlights the potential of such a runaway, twitterstorm. We conducted a sentiment analysis of tweets since 2006 focusing on silver, titanium and carbon-based nanomaterials. We further examined the sentiment expressed following the decision by the European Food Safety Authority (EFSA) to phase out the food additive titanium dioxide (E 171). Our analysis shows an engaged, attentive public, alert to announcements from industry and regulatory bodies. We demonstrate that risk governance frameworks, particularly the communication aspect of those structures must include a social media blueprint to counter misinformation and alleviate the potential impact of a social media induced regulatory and economic reaction.

Received 27th December 2021
Accepted 31st March 2022

DOI: 10.1039/d1ra09383e

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## Introduction

Over the last few decades, there has been a considerable focus on nanotechnology governance. Currently, there are three EU Commission funded projects centred on the establishment of both a risk governance framework and council, namely RiskGONE,† NANORIGO‡ and Gov4Nano§. Governance implies more than simple rules setting, legal instruments and regulation, it is a process that affords the engagement, of some degree, of multiple stakeholders into any governance regime. Governance also implied an understanding of the needs and emotions of both stakeholders and citizens. This provides the motivation for this work on how nanotechnology risk is represented on twitter. Indeed, the concept of governance speaks to the need for a more democratic process to be put into place around rule setting with regard to, in this instance, nanotechnology related activity. Hasfi *et al.* (2021) make an explicit link between social media and what they refer to as democratic opportunities.[1] The creation of an inclusive architecture to house debates around the future of nanotechnology is one of the key challenges for public policy around structures and policy instruments that speak to the concerns of the so-called lay populations. Our work goes some way in facilitating this, offering a valuable contribution both empirically and in terms of methodology in understanding risk perception as expressed on social media. Overall, our objective is to afford those engaged in risk governance around nanomaterials a more *inclusive* set of methods for capturing risk perception around nanotechnology related activities. There has been much debate around the need for societal acceptance around emerging

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† https://riskgone.wp.nilu.no.
‡ https://nanorigo.eu.
§ https://www.gov4nano.eu

technologies.[2,3] This is true with regard to practices such as human genetics, Genetically Modified Organisms (GMOs) and more recently, artificial intelligence.[4–6] One of the persistent challenges relates to how to allow or even encourage the public to be part of such debates.[7–9]

In terms of ensuring the sustainability of emerging technologies, risk perception amongst the citizenry has been an important determinant.[10,11] On one level, risk perception among the public is important as it may represent a risk to companies involved in nanomaterial value chains in terms of reputational risk and attendant political/regulatory risk. Beyond this rather instrumental view, knowledge of risk perception among the public is also crucial in the construction of a risk governance framework and governance council.[12–14] High levels of public anxiety imply the need for more robust risk governance processes[15] and if we are able to detect specifics sets of concerns, this will allow for a greater focus on the part of any nascent risk governance framework or indeed governance council.

The evidence on public attitudes toward nanotechnology remain somewhat scant.[16] Over the last decade or so, we have seen outputs from focus groups that have included a variety of stakeholders. Such focus groups have been made up of mainly interested professionals.[17] There have also been studies of media coverage of nanotechnology whilst these may be something of a proxy for public opinion they do not constitute 'actual' public opinion. This study addresses this data lacuna and seeks to broaden our understanding of opinions around nanotechnology. It posits a set of methods for scientists working on the phenomena of risk perception around emerging technologies.

The paper analyses ten years of twitter data around three distinct nanomaterials, nano-silver, carbon nanotubes and titanium dioxide. We use a sentiment analysis protocol to gauge public attitudes towards this emerging technology.[18,19] Our data allowed for a both longitudinal and comparative analysis with which were able to detect temporal 'hot spots' over a 10 year horizon and provide evidence of different attitudes towards distinct nanomaterial related processes. Where we detect such 'hot spots' we extract relevant texts and identify what type of issues drive elevated risk perception. Thus, we are able to provide a valuable input in the creation of both the risk governance framework and the governance council as posited by the NMBP-13 family of consortia. Here, NMBP denotes "Nanotechnologies, Advanced Materials, Biotechnology and Advanced Manufacturing and Processing" and NMBP 13 refers to a specific research call on the part of the European Commission to create a risk governance structure around nanotechnology related activity. This paper also captures the fall-out on social media of the 2021 decision by the European Commission to phase out the use of Titanium dioxide E 171 from food. The European Food Safety Authority (EFSA) had updated its safety assessment of the food additive titanium dioxide (E 171), following a request by the European Commission in March 2020.[20]

Our work demonstrates an amplification effect around negative twitter thread. The seminal work of Kasperson on the social amplification of risk provides an effective theoretical backdrop.[21] Moreover, what has been termed "dread risk" has a strong basis in the risk perception literature dating back to work by Slovic and others.[22] Here we see a close link between the phenomena of dread risk close and lay opinion. This is echoed in, Jagiello and Hill who also tie this notion of *dread* to the amplification of risk.[23] Furthermore, we find that public discourse around nanotechnology is quite distinct from that of expert opinion. Generally speaking, communications from official source is often accompanied by a degree of suspicion from other platform users.

The Covid-19 pandemic has again brought into sharp relief the differences between expert and lay opinion on science. Moreover, it has shown how profound the downstream consequences of such differences can be. Holistic risk governance regimes should ideally factor in some of these negative effects and address the stark differences that exist between objective and subjective risk. Understanding the manner in which wider societal risk perceptions are created is part of this process. Currently one of the areas not sufficiently addressed by the NMP 13 group of consortia is precisely how this process unfolds on social media. Again, to return to the case of the Covid-19 pandemic, it is clear that social media has had a major impact on the wider public attitude towards, for example vaccines. Sources of information and news has changed profoundly over the past two decades and it is clear that any risk governance frameworks, including a council will come need to engage with new forms of communication including social media.

One question that arises is why it matters what opinions exist among lay populations? There are a number of vectors whereby public opinion can impact upon the sustainability of the nanomaterials industry. One is through the political process and it may manifest itself in the form of regulatory risk. Another is related to the general public opinion impact that may have on key stakeholders. We have in mind here two main groups, the investment community and those who work in insurance markets. These communities may have some level of knowledge around nanomaterials but still exhibit many of the characteristics of a lay population. In the case of insurance, a change of risk perception among the underwriting community could have profound effects on nanomaterial related activity if insurability becomes an issue. Baublyte *et al.* showed that whilst the insurance community did exhibit a better level of understanding of nanomaterials than the public there was still a good deal of uncertainty present.[24] Given the *embeddedness* of this professional group in wider society, changes in risk perception among the general population will have an impact on this group. Thus, such changes could have an impact on the sustainability of the nanomaterial industry. Thus, we make the case that general public opinion around nanomaterials is an important variable. In this context, Murphy *et al.* made the case for improved communication between the nanomaterial sector and the insurance industry in order to counteract this set of risks.[25]

Risk governance processes have a number of outputs and multiple end users and should speak to the overall sustainability of an activity. Given the dynamics outlined above, understanding risk perceptions as expressed in social medial would improve this process. It would allow stakeholders to detect changing narrative around certain technologies. The methodology presented allows the detection of changing attitudes across time. This allows stakeholders to get a temporally specific readout on risk perception and sentiment allowing for a more precise readout in terms of what we might term political risk. That said, the risk governance process or indeed the set of approaches outlined in this paper should not be in the service of solely reducing political or regulatory risk. Nor should there be an implicit top-down assumption that lay opinion is a phenomenon that needs to be managed. A better understanding of risk perception as expressed on social media is useful for a variety of stakeholders. For those engaged in advocacy it offers the prospect of more evidence-based interventions. Besha *et al.*[26] (2020) provide a substantive set of examples where there is legitimate concern on the part of civil society over the use of engineered nanomaterials. The call in the paper for distributive justice and evidence around a lack of *voice* on the part of civil society all speak to the potential importance of social media as a forum for expressing concern. The importance of a wide geographical capture of the social media content is also highlighted by Runge *et al.*[27] These authors also have twitter as the focus on their study on public discourse around nanotechnology.[27] make the case our understanding of nanotechnology related content is very limited. They make the case that twitter analysis allows a window into the impact of specific communication strategies adopted by State funded nanotechnology centres. Our approach is more general, it that we look at volume and sentiment across a specific period – and identify trends. There are limitations in working with twitter, one is the tendency to pick up the *twitterati* for different areas of scientific endeavour. However, the broad range of our data does mitigate this danger.

## Nano perceptions

Research by Burri and Bellucci[28] on the perceptions of nanotechnology around risk and societal benefits showed an ambivalence towards the potential environmental and health risks. The same research showed that citizens were positive on the potential economic payoff through job creation and innovations in product development and potential innovations in medical technology. Later research by Gupta *et al.* supported the notion that non-experts are somewhat ambiguous on nanotechnology risks but supportive of the utility of nanotechnology to benefit society albeit with some concerns on ethical issues.[29]

In the absence of an adverse event involving nanotechnology that has widespread coverage in mainstream and social media, research in the area of nanotechnology risk has moved ahead to consider regulatory and risk governance frameworks. This is in the context of a maturing of the technology and widespread application of nanomaterials in industrial and consumer products. In a regulatory setting, the EU's chemical legislation, registration, evaluation, authorization, and restriction of chemicals (REACH) consider nanomaterials as special form of a chemical substance with the term nanoform being used to distinguish between nanomaterial characteristics such as size, shape and coating.[30] Multiple governance frameworks have been developed to provide a toolset for the independent governance of nanomaterial risk taking the views of a variety of stakeholders into consideration.

Isigonis *et al.* provide one such solution *via* a Risk Governance Council (RGC) that is flexible to the needs of emerging nanotechnology while serving as a communication tool for stakeholders.[31] The proposed RGC compartmentalizes the risk governance into five discrete, consecutive phases, pre-assessment, appraisal, characterization/evaluation, management and communication. The latter phase is of particular importance in the context of this article where the RGC will "*provide communication with stakeholders and civil society, based on high quality information*" (ibid). The methods adopted in this paper offer a contribution in this regard as they provide important context to the task of risk communication.

Using a Social Life Cycle Assessment (s-LCA) and Multi-Criteria Decision Analysis (MCDA) Subramanian *et al.* examined the social impact of nanotechnology innovations and calculated the benefits and costs to each stakeholder.[32] Based on a case study, they (ibid) suggested country level information on social indicators in support of nanotechnology risk governance. In a different paper, Isigonis *et al.* reviewed thirty-six tools on risk governance and several risk governance frameworks and, based on their analysis, recommended specific methods to improve existing risk governance tools "*so that they can communicate, evaluate, and mitigate risks more transparently*".[33] They (ibid) point out that many of the models/tools require some kind of specific, sectorial expertise and concede that "*whether the information is understandable for the target audience or not remains an open question*".

In short, research on public opinion demonstrates either an absence of an understanding of nanotechnology or an ambivalence on the societal benefits and potential risks. Significant private and public research resources have been expended on risk governance tools and, while there is still much to be achieved, there is a growing consensus on the important attributes of such frameworks and the governance of these frameworks. One common aspect of the frameworks is the requirement for effective communication to a variety of stakeholders from regulators to manufacturers to civic society. However, despite these advances, any appraisal of communication strategies exposes the fact that the communication of risk information is likely to be understood by those with some expertise in nanotechnology. Furthermore, the communication of nanomaterial risk from a governance council or similar body is unlikely to be equipped to counter information and misinformation on social media. In particular, given an adverse event triggered, or perceived to be triggered, by nanotechnology, we would argue that it is unlikely that existing or proposed communication frameworks will be adequately prepared to meet the challenges of a social media storm.

The implications of such a scenario are wide ranging. While a social media storm is likely to abate after some period, there may be long term commercial implications. This may take the form of an imposition of a strict precautionary principle by regulators or by the withdrawal of insurance coverage by insurers. The economic and social cost of these actions are difficult to discern but are likely to be profound.

## Twitter as a proxy for social perceptions

Twitter, more than any other digital medium, has become a platform from which members of civil society can make their voices heard and often generate enough influence to demand substantive change. This has caused a realigning of social capitals and power structures within public communications to which organisational stakeholders must pay attention. Thus, it has allowed for more vibrant conversations around emerging technologies such as genetics, AI and indeed nanomaterials. Additionally, twitter allows visibility of public concerns on specific subjects in real time[34] so provides a rich environment for sentiment analysis,[1] and is therefore an important method of understanding emotional responses to societal events.[19]

The act of participating or simply following a conversation is an attempt to resolve an issue that concerns that actor. Hence, the relevance to the idea of risk governance – where the notion of "concern assessment" is gaining traction.[13] Active tweeters should be taken to be active stakeholders as they have the will to promote change by addressing more passive actors who are engaged within a specific topic but are slow to react. This "inactive public" can have low levels of knowledge in a subject but are interested, and so do meet the definition of stakeholders, although they may not recognise that stakeholder role themselves.[35] This silent majority of public stakeholders will monitor a subject but will only participate if and when they are triggered by the narrative going in a direction with which they are not happy. For instance, Díaz and Henríquez, demonstrate a direct link between people under lockdown and pessimistic twitter search queries.[36] This is an important part of the overall picture for an inclusive risk governance project. A twitter engagement starts as a quest for understanding but if no clear resolution is found actors will start to signal their frustration. When the passive stakeholders become frustrated enough to become active this can quickly coalesce into a campaign of resistance, and once an issue starts to develop into a campaign it is difficult (for either internal or external parties) to ease the momentum. This makes twitter content a useful resource for those interested in creating risk governance frameworks.

In the wider accountability discussion Manetti and Bellucci assessed if social media is an effective mechanism for stakeholder engagement, finding that while only a small number of organisations use it in a deliberate fashion, social media including twitter is a useful source of divergent views where stakeholders are given voice but are not often allowed transformative power.[37]

Willis shows that through twitter, simmering discussions with moderate local attention can suddenly gain international public interest.[38] The resulting combination of domestic and international pressure can, in some cases, quickly force legislative change. Twitter sentiment detection and classification has become a major research tool as it successfully gauges emotions and opinions in detail not possible before social media became ubiquitous and allows real time insights during critical events.[19,36,39] Kumar and Jaiswal undertook a literature review of sentiment analysis on twitter and found it to be a powerful tool in assisting decision making.[40] Currently, there is only sparce twitter sentiment research that specifically relates to Risk Perception of Nanotechnology. Runge *et al.* ran a census and sentiment analysis of nanotechnology-related tweets and found a self-organising online network of lay-people and experts, that they suggested would have significant affect how nanotechnology and science in general could be communicated informally.[41] Veltri also used sentiment analysis to extrapolate public perceptions and attitudes toward Nanotechnology on twitter, founding that negative sentiments were largely based on uncertainty and fear of the unknown rather than taking the form of open hostility.[42] Similarly, Jun *et al.* used sentiment analysis to look at lay-opinion of GMO-related information posted by organizations on twitter, they found that the information releases generated strong discussion among stakeholders including consumers, producers and policymakers, and stated that while public opinion is influenced by news topics there were significant shifts in emotions toward GMO over time, but interestingly, those shifts could be temporary as after the campaign subsides, sentiment often reverts back to previous normal values.[43] Twitter produces a discussion that would rarely occur on traditional media platforms.[40] So, whether the subject is of mainstream public concern or of interest to a more finite lay-group, there can be equally high impact during the twitter campaign, therefore, the mass of the "*twitterstorm*" has more impact than the volume.

Digital technology enables organising at a grassroots level in a way that is fast and fluid, actors can organise without an organisation into what is often also a leaderless "adhocracy" with little or no institutional leadership, which means there is an absence of network internalities and the clear objectives that would develop within traditional organisational processes.[44] This makes digital campaigns difficult to engage with, highlighting the importance and usefulness of gauging public perceptions as they form. Individual twitter posts, particularly those with low engagement (*i.e.* likes, replies, or retweets) could seem unimportant, however, referencing Bourdieu's assertion that the daily and banal can sometimes be pregnant with meaning, in the case of twitter, the 'banal' posts can provide a deep insight into public sentiment.[45] Twitter is the preeminent forum for public voicing and can be an accurate gauge of risk perception within civil society, the importance of lay engagement is a normative commitment recognised as a core part of science governance within democratic societies to ensure public understanding and buy-in to new scientific developments.[46] Hasfi *et al.* note that while governmental/organisational engagement is often structured as data gathering rather than a first step toward an actionable response, these civic engagements can cause a reversal of roles where the community begins to take the lead in the discourse, acting as advocates, not only bringing the discourse in a positive direction but also working to find solutions to underlying problems. Instead of being used a one-way communication tool, social media must be treated as a platform for openly engaging in meaningful dialogue with citizen stakeholders,[1] and this engagement should be adopted from as early a stage in the process as possible. Systems to harness real-time data need to be built into organisational risk governance processes so immediate responses or assistance can be provided to vulnerable citizens.[34] Many organisations use Customer Relationship Management (CRM) software to monitor sentiment in real-time across multiple media, allowing organisations and expert stakeholders to be proactive in discerning lay-opinion immediately and address concerns. Building social media engagement into governance processes enables; understanding of public opinion and use of that information to prepare for impending events; fast validation of facts so organizations can respond during and immediately after an event; post-event stakeholder community discussion, sharing information and coordinating efforts.[39]

# Methods and materials

We employed a data capturing and sentiment analysis methodology to identify the extent of existing social media activities and debates/dialogue. The longitudinal and multi-vector analysis provides important evidence of previous and current activity. By selecting specific examples we provide an important context for understanding the extent of the citizen voice *via* social media.

### Data collection

Tweets written in English language, containing specific keywords dating from 2006 to 2020, were collected (Fig. 1). For tweet collection, twitter provides an API. Twitter API lets us gather tweets circulating around a specific topic. It consists of a set of programmatic endpoints, which can be utilized to access twitter data and the conversations happening on the platform.

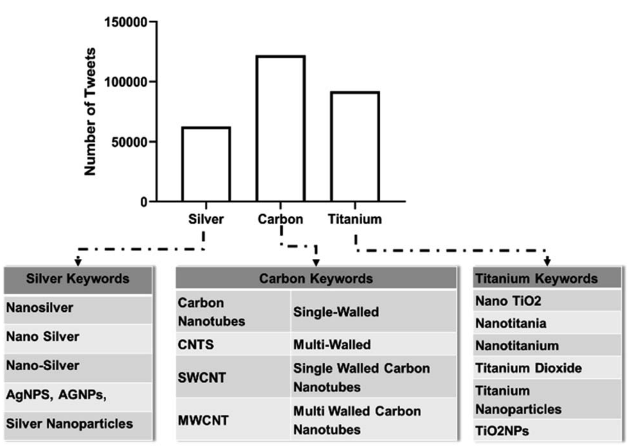


Fig. 1 Number of tweets, containing the keywords used for collecting tweets related to silver, carbon and titanium nanoparticles from 2006 to 2020.

A total of 276 983 tweets were collected containing 122 047 tweets of relating to carbon, 62 762 tweets related to silver and 92 174 tweets about titanium. It is evident that carbon nanotubes witnessed the highest number of tweets in comparison to other keywords.

### Data preparation

Data preparation and cleaning is required, especially when working with a social media dataset.[47] Many tweets were of a commercial nature and some of the keywords had similarities with twitter slang. Fake and bot accounts were omitted from our dataset following a number of steps: Tweets for each user were first counted and if the number was high the users and tweets were checked, and those that were bot accounts deleted. We counted the most used words in our data set and deleted tweets with meaningless words. Spam tweets were also deleted. See Table 1.

### Sentiment analysis

Sentiment analysis is a process, mainly using natural language processing and text analysis, that lets us know whether a certain written text carries a positive, negative or neutral tone. This allows us to understand the public opinion around a specific issue. This requires a large collection of textual data that can be provided *via* social media.

We used the state-of-the-art Vader sentiment scoring method. This method has a knowledge-base that maps every word, idiom, and emoji to a sentiment score between −4 to +4, −4 for the most negative, and +4 for the most positive sentiment. It also considers negators, multiword expressions, and all-caps writings in its score-mapping system. Finally for each body of text, *e.g.* sentence, paragraph, or tweet, average of the scores all normalized into the range between −1 to +1.[48] We used VADER code available in GitHub¶ to calculate the sentiment score of each individual tweet. These scores afford the opportunity to analyse public opinion and understand the

Table 1 Text statistics for all the tweets from 2006 to 2020

| Text statistics | |
|---|---|
| Words | 5 252 429 |
| Words (MS word) | 4 436 594 |
| Characters | 35 035 441 |
| Sentences | 453 524 |
| Lines | 277 221 |
| Paragraphs | 277 166 |
| Numerals | 569 187 |
| Punctuation | 2 515 751 |
| Average read time | 437 hours 42 minutes 8 seconds |
| Average spell time | 583 hours 36 minutes 11 seconds |
| Pages (A4) | 10 505 |

¶ https://github.com/cjhutto/vaderSentiment.

correlation between the events that stir up conversations about these words and how they affect the general population's opinion on specific matters.

## Results

Fig. 2 shows the number of tweets per element, colour-coded to distinguish between positive, negative, and neutral tweets. Since many tweets are declarative or simply news, they lack sentimental value. The number of these neutral tweets is higher than positive or negative ones.

Fig. 3 is showing the number of tweets per year from 2006 to 2020 for each element. The most noticeable feature of this graph is the peak for silver tweets happening in 2014, which will later be explained.

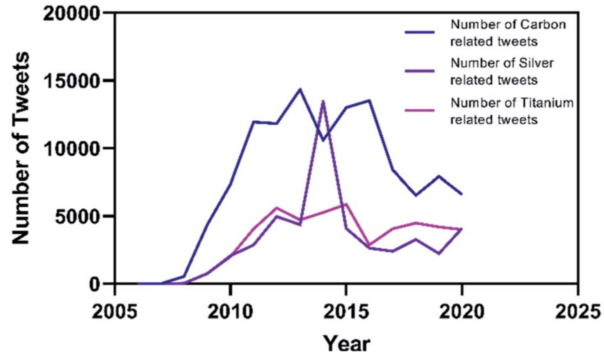


Fig. 3 The volume of tweets per year from 2006 to 2020.

### Silver

Fig. 4 shows the number of tweets per year for nanosilver. This figure shows a sharp increase in related tweets in 2014 while, concurrently, we see an abrupt decline in sentiment scores for the same tweets (Fig. 5). This shows an inverse relationship between tweet volume and sentiment scores in the year 2014.

From a qualitative analysis, we believe that this activity is associated with the use of nanosilver as an Ebola treatment during the outbreak in Africa. The slight increase in positive sentiment scores in 2016 and 2020 is also noticeable. Again, from a qualitative analysis, we deduced that the year 2016 witnessed an increase in using the words antibacterial, toothbrush and whitening. In 2020, the words colloidal silver, coronavirus, masks and antimicrobial were also mentioned more frequently. We attribute this to the use of hygienic masks since the COVID-19 outbreak. General opinion towards masks armed with nano filters and colloidal silver was one of the things that people believed to be suitable protection against infection.

To expand, on March 23rd, 2014, the World Health Organization (WHO) was notified of an outbreak of Ebola virus disease (EVD) in Guinea. On August the 8th, the WHO declared the epidemic a "*public health emergency of international concern*".[49] As confusion and panic arose in the public during the initial outbreak of the Ebola virus, two Americans contracted EVD in a west African country, and the use of experimental drugs became a topic of debate as a result. Zmapp, which at the time was not licensed is one of these drugs that contains a combination of three "humanized" monoclonal antibodies (mAbs) against the EBOV GP protein. Zmapp got sanctioned after a WHO meeting addressing this matter.[50–52]

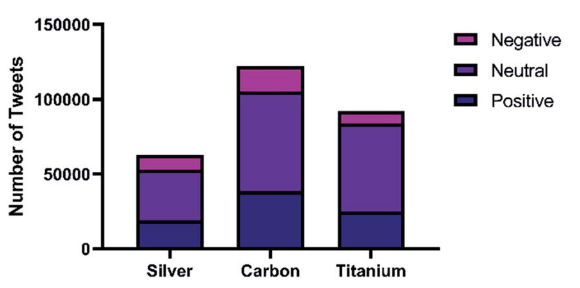


Fig. 2 The number of positive, negative and neutral tweets per element.

Nanosilver, was proposed by the Nigerian government as an alternate experimental drug for the treatment of EVD, presumably to control and ultimately neutralize widespread fear. However it violated the USA Federal Food, Drug, and Cosmetic Act,[53] and was claimed to be a pesticide by some groups.[54] Soon after, the Nigerian government rebutted its earlier statements.[55]

Naturally, concerns were voiced on social media during this period. This is evidenced in the tweet sentiment scores in the year 2014, pinpointing the most used words in tweets and recovering some of the tweets containing those words. These tweets were both for and against ZMapp and nanosilver and expressed strong and emotional opinions without and obvious evidence of expertise. Rather, the opinions were self-propelled based on existing tweets. This heated discourse on social media is likely to have contributed to actions taken by government regulatory agencies such as Nigeria's National Agency for Food and Drug Administration and Control (NAFDAC), highlighting the individual's role in determining national and global actions.

### Titanium

Table 2 shows the most prevalent words used in tweets per year with the frequency of the words 'zinc' and 'sunscreen' being notable.

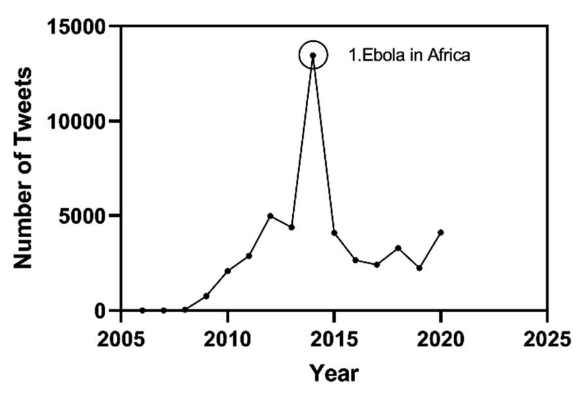


Fig. 4 The volume of silver-related tweets from 2006 to 2020.

 

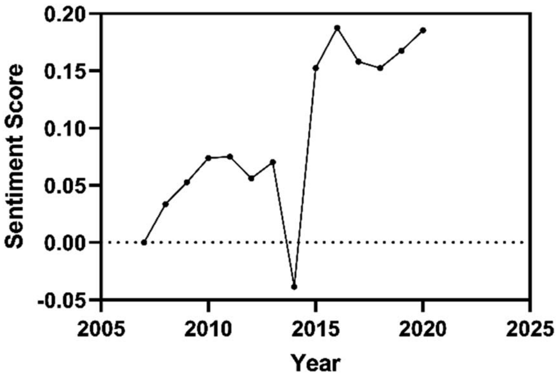


Fig. 5 Sentiment scores of silver-related tweets from 2006 to 2020.

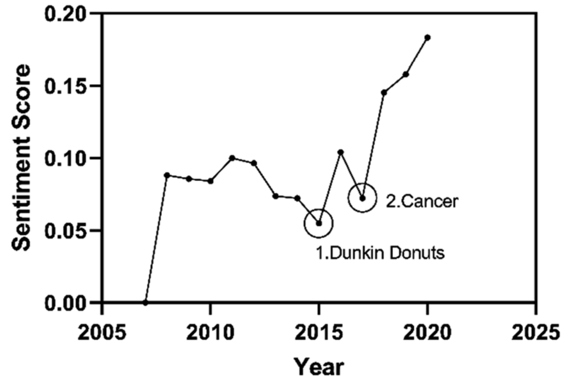


Fig. 6 Sentiment scores of titanium-related tweets from 2006 to 2020.

Table 2 Titanium frequent words. This table shows the most frequent titanium-related words by year

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 2009 | **Zinc** | **Sunscreen** | Safe | Vitamins | Human |
| 2010 | **Sunscreen** | **Zinc** | Paint | Mustard | Honey |
| 2011 | Iron | Flat | **Zinc** | **Sunscreen** | Mineral |
| 2012 | **Sunscreen** | **Zinc** | Irons | Hair | Skin |
| 2013 | Iron | **Zinc** | **Sunscreen** | White | Food |
| 2014 | Food | White | **Sunscreen** | Dressing | Yogurt |
| 2015 | Donuts | Dunkin | Food | Powdered | **Zinc** |
| 2016 | Market | **Zinc** | Food | **Sunscreen** | Iron |
| 2017 | **Zinc** | Food | Global | **Sunscreen** | Cancer |
| 2018 | **Sunscreen** | **Zinc** | Market | Skin | Paint |
| 2019 | **Zinc** | Sunscreen | Food | **Sunscreens** | Ingredient |
| 2020 | **Sunscreen** | **Zinc** | Sunscreens | Mineral | Skin |

"Zinc" and "sunscreen" provide protection against the adverse effects of both UVB and UVA radiation[56] and minerals like zinc oxide (ZnO) and titanium dioxide ($TiO_2$) are frequently used as inorganic physical sun blockers.[57] In this context, a comparison between "zinc oxide" and "titanium dioxide" has been a matter of social media discussion from the start of our data collection. Centred on 2017, there was a heated and predominantly negative reaction to the news that Dunkin Donuts was removing titanium dioxide from powdered sugar glazing on their donuts. Most tweets expressed come outrage that titanium dioxide was used in the first instance. Similarly in 2017, a further increase in negative tweets centred on the use of titanium dioxide in cosmetics and sunscreen products. The catalyst for this negative reaction was the news that the proposed classifying titanium dioxide as a carcinogen. Sunscreen is common product and there is a constant steady state conversation that debates and compares different products. The active ingredients of these products forms a significant component of that debate.

Fig. 6 shows the sentiment scores of tweets related to titanium. We can observe a general rise in sentiment scores, growing somewhat from 2007 to 2020.

From our qualitative analysis, we find that a 2015 conversation about Dunkin doughnuts using titanium dioxide in their food,[58] was the predominant cause of a score drop from 0.06 in 2014 to 0.04 in 2015. In 2017 the Committee for Risk Assessment (RAC) of the European Chemicals Agency (ECHA) concluded that $TiO_2$ met the criteria to be classified as a substance suspected of causing cancer (category 2) if inhaled.[59] This increases the sentiment score on twitter.

### Carbon

The large volume of carbon tweets resulted in a steady graph without significant fluctuations. We therefore categorized tweets into two groups based on their sentiment scores; keywords were detected and assigned to each category.

Solar power and alternative energy was seen in a positive contexts while cancer and asbestos as negative. It is worth mentioning that twitter users are not all experts, and in fact, most tweets are not based on well-researched facts and theories. Twitter is still used mainly for entertainment purposes, much more than for any weighty political or scientific matters. The release of the Iron Man movie had users disputing over the use of carbon nanotubes in the character's costume. Many tweets are also deliberate in nature but concern currently non-existent hypotheses such as the production of a space elevator, a system meant to transport humans and/or animals from earth to space, and the use of carbon within this space elevator's structure.

### Ban of titanium dioxide as a food additive

In 2021, EFSA updated its safety assessment of the food additive titanium dioxide (E 171), following a request by the European Commission.[20,60] This will see the phasing out of E 171 during 2022. Titanium dioxide E 171 contains at most 50% of particles in the nano range (*i.e.* less than 100 nanometres) to which consumers may be exposed. This announcement precipitated a spike in the number of tweets containing titanium dioxide. Focusing on the time window in which the news was spreading from September 20th to October 20th (there were no tweets prior to this window). We collected tweets containing the following key words: "E171", "titanium dioxide", "nano titanium dioxide". Fig. 7 presents the number of tweets per keyword. It is observable that titanium dioxide is used more repeatedly in tweets.

As for sentiment scores shown in Fig. 8, E171 had the lowest, and the tweets prominently leaned towards more negative sentiment scores.

The banning of titanium dioxide ($TiO_2$) demonstrates the bilateral relationship between twitter activity and global news. In 2014, users expressed concern about the use of nano-sized $TiO_2$ in dairy products such as yoghurt and milk as colour enhancers. In June and again in December, many news outlets published expansive articles on the matter, heightening public interest and apprehension and thus, social media. Then there was Dunkin' Donut announcing that they would no longer be using $TiO_2$ as artificial colouring, leading to some outrage, as the public was unaware that $TiO_2$ was being used as an ingredient in the first place.

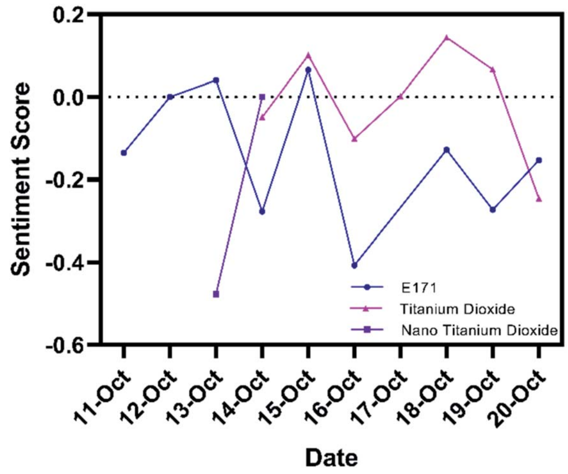


Fig. 8 Sentiment scores of titanium-related tweets from 2006 to 2020.

## Discussion

In this section, we pull together the key points of the article. These are;

• A key function of a nanomaterial governance framework is communication. Currently this communication is largely through expert networks.

• The public perception of nanomaterials is a mixture of ambivalence or mildly positive with that positivity focused on economic and societal benefits.

• Twitter affords all citizens the ability to participate in public discourse but localized, low latent issues can quickly develop into a twitterstorm with the potential to activate regulatory responses and economic harm.

• Social media research can afford risk governance processes an important insight into lay opinion.

• In this research we used a sentiment analysis tool to examine 270 000 twitter posts relating to silver, carbon and titanium nanomaterials.

• The sentiment score is generally low-positive which is consistent with prior research on the public perception of nanomaterial.

• However, we find that in two instances, nano silver (Ebola crisis) and titanium dioxide (food additive), the sentiment scores turned negative quite quickly.

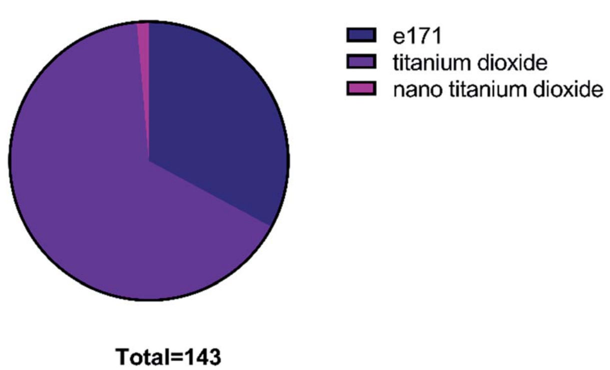


Fig. 7 Number of tweets per keyword from 20th September to 20th October.

The first notable detail is that there has not been a breakout or runaway story involving nanomaterials that had a global impact. However, we note some tell-tale twitter characteristics involving nanomaterials tweets that could portent a twitter-storm. First, there is a triggering event. Almost by definition, it is impossible to predict that event. What is clear is that a positive story will have little impact but a negative event immediately increases the volume of tweets and simultaneously decreases the sentiment score. The twitter dialogues that we evidenced did not scale up to be global stories with significant, longstanding consequences but we do see clear evidence of an absence of an expert voice in the discussions. Indeed, where there is governmental or regulatory involvement, the twitter posts tend to view that interaction with some suspicion.

What is clear from our analysis is that there exists a public discourse that is quite divorced from expert communication and equally unlikely to pay much heed from an expert risk governance council unless the expert opinion is organised and trained in social media use. Scepticism around official discourse is now ubiquitous and any truly inclusive risk governance process needs to find protocols to engage with non-expert communities. Similarly, while proposed risk governance frameworks include communication as part of their remit, that communication is seen from the prism of expert-to-expert dialogue. In this environment, the research, commercial and societal benefits of nanomaterials could be quickly in jeopardy if a twitterstorm takes over the public consciousness.

Veltri used a similar mature methodological approach to nano-tweets without focusing on specific nanomaterials, but in nano in general.[42] According to the authors' findings, nanotechnology is not a topic of discussion on twitter, but rather knowledge is transmitted and disseminated by a small number of “power users” who are heavily “followed”. Negative emotions, according to the author, are more closely linked to uncertainty and fear of the unknown than to hatred.

With a similar approach, Singh *et al.* found that there are many positive sentiments associated with the subject nanotechnology, such as trust in the technology, anticipation about the outcome, and joy about the availability of the predicted applications, which far outweigh the anger associated with nanowaste, mistrust about failures to meet targets, and anger associated with wasting tons of taxpayers' money on nanotechnology projects.[61]

## Conclusions

There has been a concerted effort by experts in the field of nanotechnology and by national bodies to create a governance framework or governance council to address potential nanomaterial risks. The stated purpose of these frameworks is to provide risk appraisal, management and communication. The communication aspect of that role is of paramount importance but to-date, that communication is largely between expert groups. Social media, and in particular twitter, have the potential to overwhelm any communication strategy proposed by a risk governance council.

Our work as represented in this paper offers a method for better understanding risk perception around emerging technology on social media. Going forward, it offers a manner to capture *concern* as expressed on social media, in this instance twitter. For scientists working on this challenge of creating inclusive risk governance processes our work is a step forward and offers a pathway out of more traditional approaches such as focus groups. That said, this is not a panacea for this set of problems and it is certainly not a replacement for the voices of NGOs and consumer advocacy groups. Considered opinion from such bodies should not be trumped by proxy public opinion metrics derived from social media data. Moreover, the nature of social media in general and twitter in particular is such that general public opinion is often hard to distinguish from both the scientists and pressure groups operating in the field as they seek to frame debates taking place in the digital realm. That said, in conjunction with other methods, the approach set out here does offer the potential to generate a risk perception *heat map* or has the potential to populate a *control banding* artefact.

In this paper, we start by highlighting existing research on the public perception of nanotechnology. We then detail the manner in which social media, and in particular, twitter, can provide the means for localized concerns to mushroom into a global issue. We then used an advanced data sentiment analysis to examine historical tweets relating to nano silver, carbon and titanium dioxide. In general, we find low, but positive sentiment towards nanomaterials but we show strong evidence that sentiment can turn sour quickly when there is a catalyst news event.

Risk governance frameworks rightly include communication as a vital function. That communication function tends to be viewed from the context of a nanomaterial expertise and, although communication to the general public is often seen as an important feature, there is no clearly strategy to operationalize that voice. If there is an adverse event involving nanomaterials, real or perceived, the public element of the discourse is likely to occur on social media platforms. Social media storms can quickly spread overwhelming any rational, expert voices. This can have real-world consequences that may result in regulatory overreach, insurance coverage withdrawal and a collapse in public confidence in nanomaterials. Policymakers and scientists engaged in risk governance should include a social media element to their communication strategy to prevent such uninformed twitterstorms.

## Definitions

We define nanotechnology as the engineering of materials with dimensions and tolerances of less than 100 nanometres.

We define nanomaterial as a substance having particles or constituents of nanoscale dimensions, or one that is produced by nanotechnology.

We define nano perceptions as the general awareness and opinion held by the public with regard to nanotechnology and nanomaterials.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work was supported by the European Union's Horizon 2020 Research and Innovation Programme under the auspices of the RiskGONE project funded under the NMBP13-2018 call [Grant No. 814425].

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