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# Corrosion, Tribology, and Tribocorrosion Research in Biomedical Implants: Progressive Trend in the Published Literature

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**Abstract** There has been significant progress in implant research during last the 10 years (2005–2015). The increase in the elderly population coupled with a lack of proper physical activity is a potential cause for the sudden increment in implant usage. Implant life and performance are influenced by several parameters; however, literature showed that corrosion, tribology, and tribocorrosion processes of implant materials are main concern and driving mechanisms in the degradation processes. There is currently a large need for research in this area. Furthermore, there has been no recent systematic literature review to analyze the progress of research and published work in this area. The objective of this work is to provide a trend in the published articles in the area of corrosion, tribology, and tribocorrosion during last century, with emphasis on the progress over the last 10 years. The paper also tries to report the current state-of-the-art research in the area of corrosion, tribology, and tribocorrosion research in bio-implants based on number of published articles. The reviews demonstrate that during the last 10 years, there has been significant progress in implant research, particularly in the tribocorrosion area, however, significantly lower than tribology and corrosion research.

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## 1 Introduction

Research in the fields of tribology, corrosion, and tribocorrosion in biomedical implants has increased in the last year due to clinical relevance in orthopedic and dental health care [1]. As the number of publications parallels research activities, the degree of contribution to the literature for medical societies is regarded as a marker of clinical performance and research productivity. Several factors may contribute to the increase in specific scientific output. The most important is the need to bridge the knowledge gaps, particularly in the medical field, which is inevitably necessary for the safer practice of medicine, academic performance improvement, and better prospects for the patient. Scientific advances in the biomedical field are most likely to arise or are most easily promoted, when basic and clinical researchers are involved with the emergence and development of new contexts, creating a translational research.

The science of tribocorrosion can be defined as a degradation process of the surface of materials resulting from the combined action of mechanical wear and chemical/electrochemical reactions [2–4]. In other words, it is the correlated study of two different scientific domains: tribology and corrosion. Tribology is a branch of mechanical engineering, which consists of the study of interacting surfaces in relative motion and includes the fields of friction, lubrication, and wear [1, 5, 6]. Corrosion is the deterioration process that converts a metal to another state, due to the chemical interaction of the material with its environment [7]. Even though the occurrence of corrosion and tribology is most common in industries such as marine, mining, aerospace, food, nuclear, chemical, and petrochemical, the fundamental mechanism and their overwhelming factors are not well understood [8–10]. Moreover, it have very strong role in the damage caused to the human joints, prosthesis, and restorative dentistry [1, 11].

There is a robust inter-relationship within the factors influencing tribocorrosion. Major factors include the property of the material, mechanics of the tribological contact, and the physicochemical properties of the environment, see Fig. 1. It has both beneficial and deleterious effects on the subject of interest. Hence, it is important to consider every aspect with equal importance while evaluating tribocorrosion. The field of tribocorrosion has grown, and more researchers from different fields of science such as medical, biomedical, and engineering give attention mainly due to the scope of application.

In biomedical research area, tribocorrosion is studied mainly by two fields viz., orthopedic and dentistry. Orthopedic and dental implants experience the synergistic effect of wear and corrosion once they become load-bearing devices exposed to body fluids on the implant-bone interface, Fig. 2 [14, 15]. Body joints are influenced by periprosthetic fluid. It has been observed that bone–implant interfaces are subject to friction, which can cause fretting corrosion with inflammatory tissue reactions [1]. In regards to dental implants, they are in contact with a complex environment known as saliva, which experiences variations in pH and temperature that increase the corrosion process of the implants. Simultaneously, dental implants are exposed to cyclic micro movements at implant/abutment and implant/bone interfaces, as shown in Fig. 3, causing a relative motion between contacting surfaces and leading to

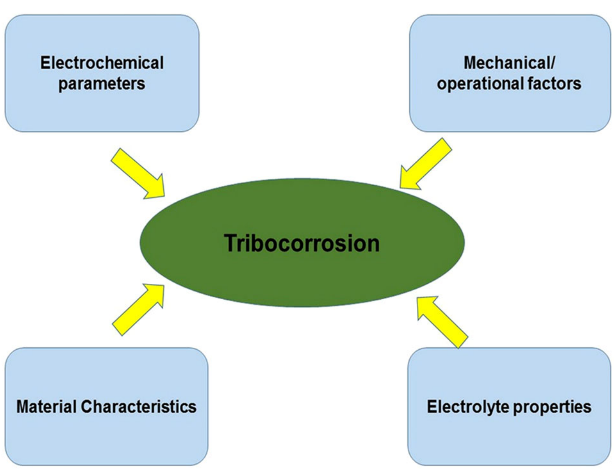


**Fig. 1** Describing the factors affecting tribocorrosion system

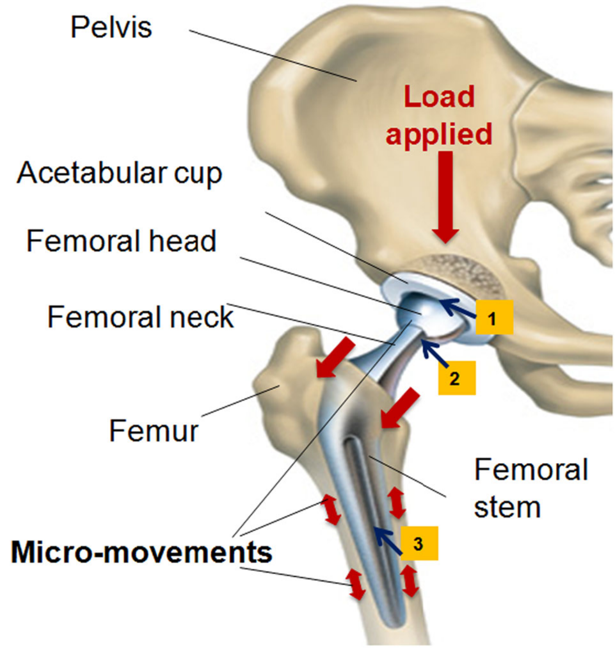


**Fig. 2** Total hip replacement (THR), demonstrating three interfaces (*1*) head-cup, (*2*) taper junctions, and (*3*) stem-bone

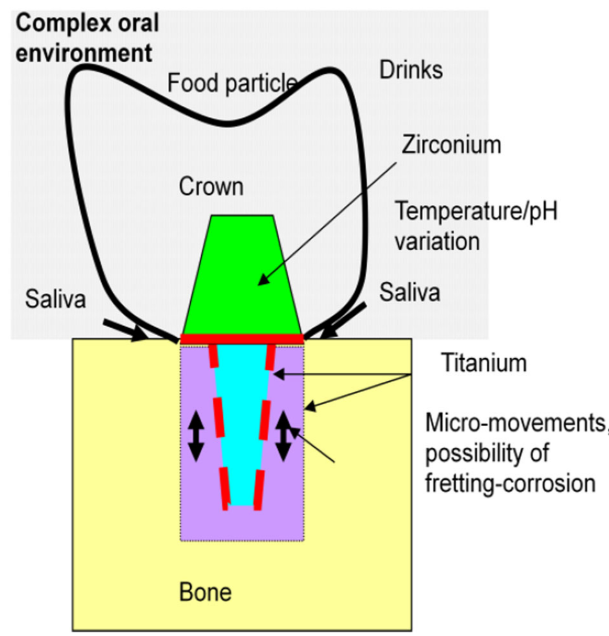


**Fig. 3** Tribocorrosion in dentistry

wear [12, 16]. Therefore, tribology and corrosion are major contributors to the premature decay of implants, and it is crucial to understand the tribocorrosion process on which the implants are submitted in order to avoid infection, necrosis, osteolysis, and, consequently, implant failure. There are increasing number of publications reporting every year on the role of various aspects such as pH, protein concentration, salivary viscosity, and biofilms on tribocorrosion [17–22].

The number of total hip replacements and total knee replacements performed in 2010 according to the Inpatient Surgery data from the US were 332 and 719 k, respectively [23]. These implants may last up to 12 years on average [16]; however, there is a history of failed innovations demonstrated by the failure or recall of some individual products, as well as whole classes of devices, such as metal-on-metal (MoM) bearings [24]. The concerns arise about the long-term stability of MoM implants due to the release of metallic nano-particles and ions having a carcinogenic potential, as well as associated hypersensitivity reactions, muscle and bone destruction, and prosthetic loosening, leaving some patients with long-term disabilities [13, 25, 26]. There are reports showing the wear map of CoCrMo hip prosthesis during tribocorrosion [27].

According to the American Academy of Implant Dentistry (AAID), 3 million citizens have implants, and that number is growing by 500,000 a year, with a success rate of 98 % [28]. The majority of failures are due to aseptic loosening and metal hypersensitivity [29, 30]. These reactions can be the result of the chronic inflammatory response to implant surface debris and metal ions released from the tribocorrosion process [31–36]. This process demonstrates that previous tribocorrosion studies are fundamental to protect patients from an increased risk associated with the introduction of new technology and materials.

In fact, there has been significant progress in implant research during the last 10 years, mostly generated due to the observed clinical problems and the need of creating new materials or surface modification that can satisfy the required demands for each application. Hence, in this work, an attempt has been made to analyze the progress of the research and the trend in published work/papers in the fields of corrosion, tribology, and tribocorrosion related to orthopedic and dental implants. An attempt has also been made to provide an overview of the scientific development that occurred during the last 10 years as well as a future forecast growth in this research area based on the published articles.

## 2 Tribocorrosion Publications: Literature Review Criteria

In order to obtain the current research available on the field of implant tribocorrosion, the databases PubMed, Science Direct, Google Scholar, Scopus, Wiley Online, Web of Science, and Springer were searched for articles containing specified key words. Four types of searches were conducted in each of the databases mentioned. Results from each database were placed into tables, and when a search had been conducted on all databases, a final table was made containing the total findings from all databases. The implants of interest were divided into the categories of dental, hip, knee, shoulder, TMJ, and spine. The articles found were then further divided into the fields of corrosion, tribology, and tribocorrosion.

As described earlier, the field of tribocorrosion includes tribology and corrosion. In addition, the tribocorrosion research in orthopedic and dental implant is progressing through specific fields which includes dental [17, 18, 20], total hip prosthesis [11, 13, 16, 37–39], knee [40, 41], shoulder [42, 43], TMJ [44, 45], and spine [46, 47]. Hence, in this study, our first search looked for the total amount of articles available in the databases with the key words *Dental, Hip, Knee, Shoulder, TMJ,* or *Spine,* followed by the keyword *Implant*, followed by *Corrosion, Tribology,* or *Tribocorrosion.* The number of articles from each database was recorded in tables in Excel. A final table was made containing the totals from all of the previous tables from each database (Table 1) and used for the final analysis.

The second search was to determine how the fields of corrosion, tribology, and tribocorrosion on implants had progressed as a whole in the past 100 years. On each site, the key words *Implant AND (Tribocorrosion OR Corrosion OR Tribology)* were entered in order to obtain articles relating to implants and to any one of tribocorrosion, corrosion, or tribology. A filter was applied to the search over the following time periods of 1900–1909, 1910–1919, 1920–1929, 1930–1939, 1940–1949, 1950–1959, 1960–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2009, and 2010-present. The data from each search were put into separate tables according to database. A final table was made containing the total articles from each time period for every database. This final table's data were then converted into a bar graph (Fig. 4a).

The third search focused on how each individual type of implant had grown over the past ten years. Each type of implant (dental, hip, knee, shoulder, TMJ, spine) was searched over any of *Corrosion, Tribology,* or *Tribocorrosion*. The search was the filtered through the years 2005 through 2015 (Fig. 4b). For example, a search may be *Dental AND Implant AND (Corrosion OR Tribology OR Tribocorrosion)* with a filter for a specified year, such as 2005. The search format is shown in Fig. 3. Wiley online had an abnormally high value for the year of 2006 for all implants compared to the other databases. As such, the data from Wiley Online were discarded for this search. The data were entered into separate tables for each database, and when all databases were searched, a final table was made containing the totals from all databases. Bar graphs were made to show the growth of all implants (Fig. 4c) as well as for each individual implant (Fig. 4d). Finally, linear

**Table 1** Total number of published articles in the fields of corrosion, tribology, and tribocorrosion related to six categories of implants (accessed in December 2015)

| Keyword | Corrosion | Tribology | Tribocorrosion | Total articles for implant | Percentage |
|---|---|---|---|---|---|
| Dental implants | 37,497 | 5165 | 669 | 43,331 | 31.04518033 |
| Hip implants | 27,353 | 10,728 | 1166 | 39,247 | 28.11913394 |
| Knee implants | 17,119 | 6493 | 552 | 24,164 | 17.31268001 |
| Shoulder implants | 12,113 | 2211 | 148 | 14,472 | 10.36869331 |
| TMJ implants | 914 | 320 | 43 | 1277 | 0.914926849 |
| Spine implants | 14,539 | 2372 | 172 | 17,082 | 12.23938556 |
| Total articles for field | 109,335 | 27,289 | 2750 | 139,574 | |
| Percentage | 78.47808331 | 19.55163569 | 1.97028998 | | |

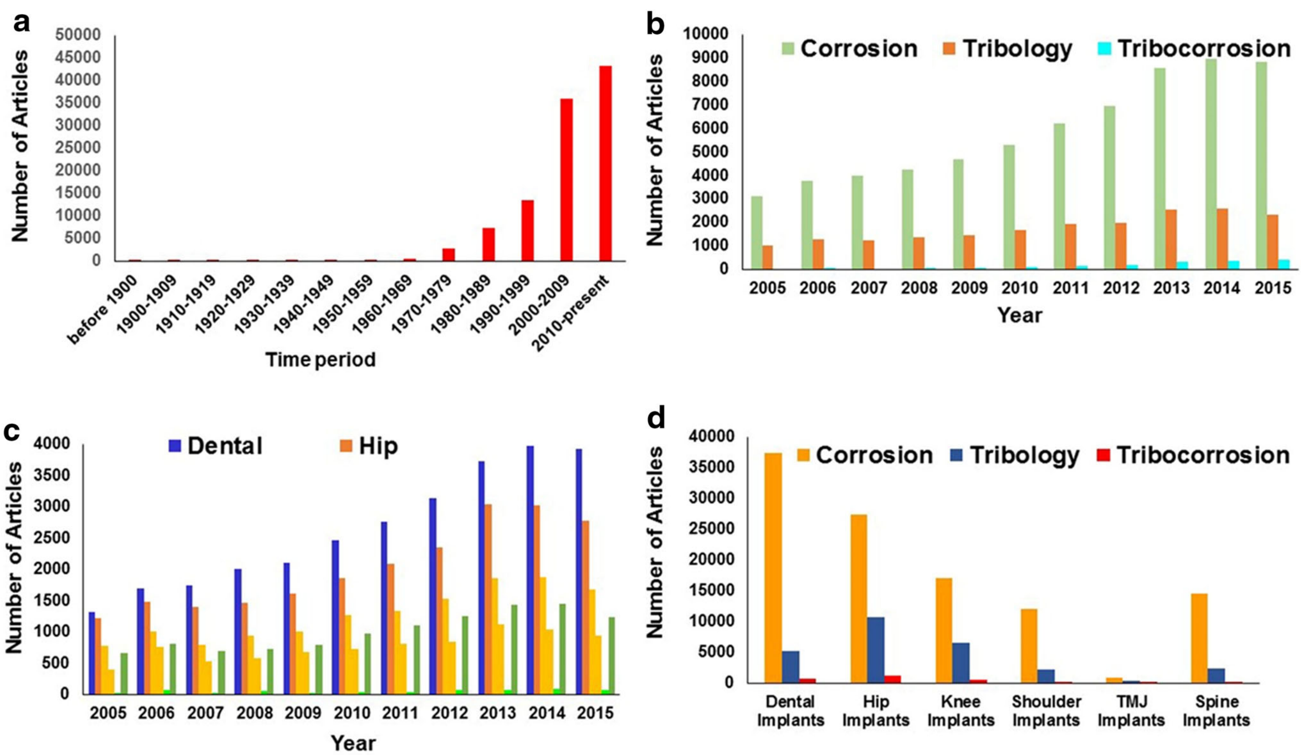


**Fig. 4** **a** Total number of published articles in the fields of corrosion, tribology, and tribocorrosion until now. **b** Total number of published articles in the fields of corrosion, tribology, and tribocorrosion from last 10 years. **c** Published articles in all of the fields of corrosion, tribology, and tribocorrosion on different implants over a time period of 10 years. **d** Number of corrosion, tribology, and tribocorrosion articles published for various implant applications

models were made for each implant based on the years 2010–2015 that predict the growth for the research of each implant until 2019 (Fig. 5 a–f).

The final search focused on how each subfield (corrosion, tribology, and tribocorrosion) has grown over the past ten years. The keywords for this search were *Implant* followed by *Corrosion, Tribology* or *Tribocorrosion.* A filter was then applied for the years 2005 through 2015. A sample search might be *Implant AND Corrosion* with a filter for the year 2005. The data were put into tables according to database with a final table made for the total of all databases. Finally, a linear model was made for each field based on the results for the years 2010–2015 that predicts the growth of the research in each field until 2020 (Fig. 6 a–c).

## 3 Progress of Tribocorrosion Research

The graphs for the current articles on implant research showed the distribution of articles between different types of implants: dental, hip, knee, shoulder, TMJ, and spine. The

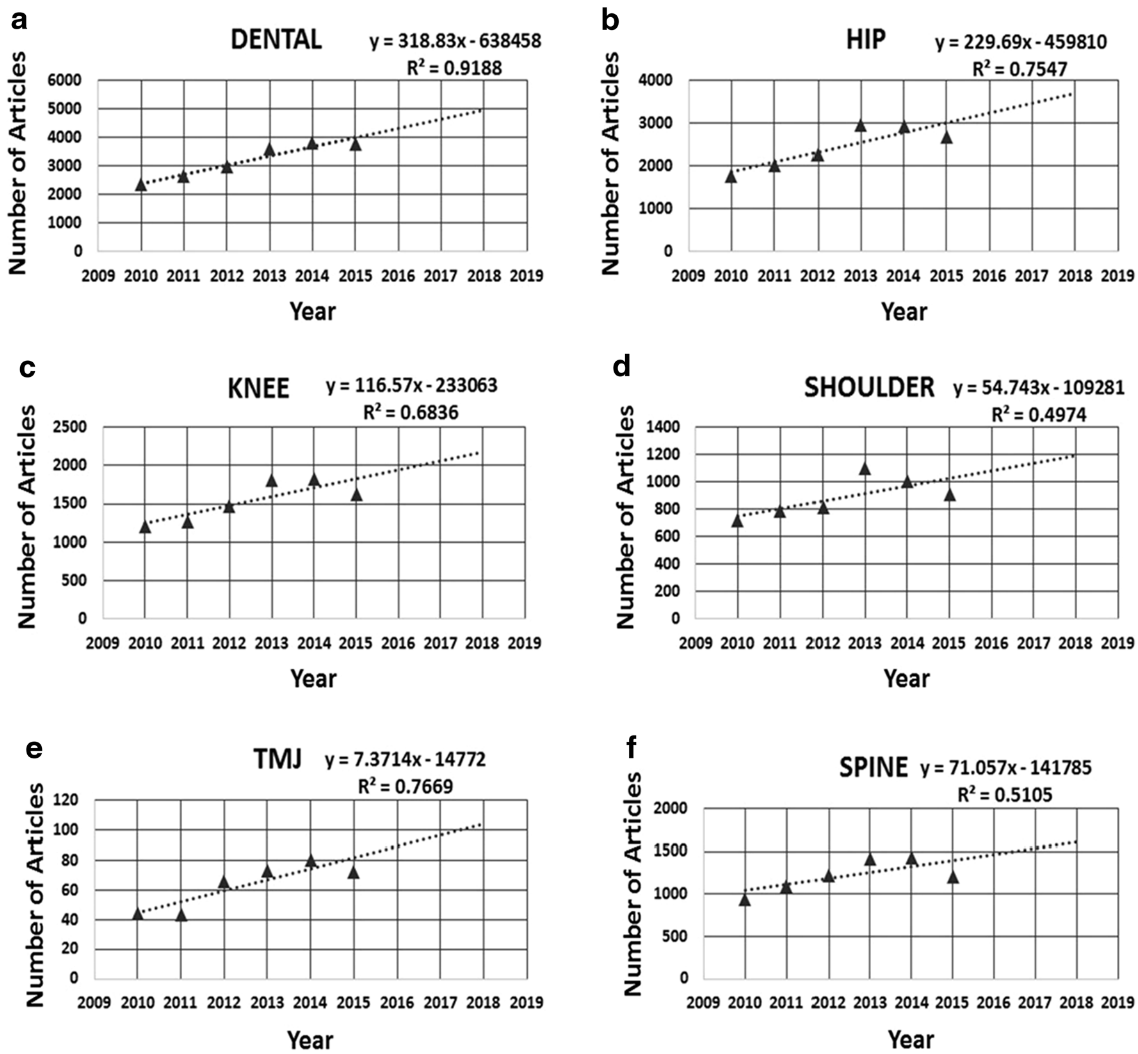


**Fig. 5** Projected growth of articles published on (**a**) dental implant corrosion, tribology, or tribocorrosion based on linear model; (**b**) hip implant corrosion, tribology, or tribocorrosion based on linear model; (**c**) knee implant corrosion, tribology, or tribocorrosion based on linear model; (**d**) shoulder implant corrosion, tribology, or tribocorrosion based on linear model; (**e**) TMJ implant corrosion, tribology, or tribocorrosion based on linear model; (**f**) spine implant corrosion, tribology, or tribocorrosion based on linear model

implants with the highest number of articles were in the dental area with 31.0 % of the articles, followed by hip with 28.1 %, knee with 17.3 %, spine with 12.2 %, shoulder with 10.4 %, and TMJ with 0.9 % (Table 1). It is probable that the number of articles on each implant is a good indicator of the relative importance given to each type, which may be directly correlated to the requirement of these implants in clinical perspective. A significant increase in the number of publications was observed in the case of dental implants and total hip implants from the year of 2005 to 2015. Approximately, a threefold increase in number of publications was observed in the case of dental implants, whereas a twofold increase in publications was seen for tribocorrosion in hip implants. However, there is not much increase in articles observed for knee and TMJ fields. These results are shown in Fig. 5e, which gives the relative number of articles for each implant in the three fields discussed.

The percentages for each of the fields were corrosion with 78.5 %, tribology with 19.5 %, and tribocorrosion with 2 % (Table 1). These results show how the study of the wear of implants is being approached. From these percentages, it seems that the majority of the focus is on the corrosion aspect of implants with some interest in tribology. Relatively few articles appear to take the interdisciplinary approach of tribocorrosion with implant research. This finding is displayed in Fig. 5; the significant differences between the fields of corrosion, tribology, and tribocorrosion are clearly observed.

The timeline for published articles also gave interesting results. Until the late 1960s, the number of articles

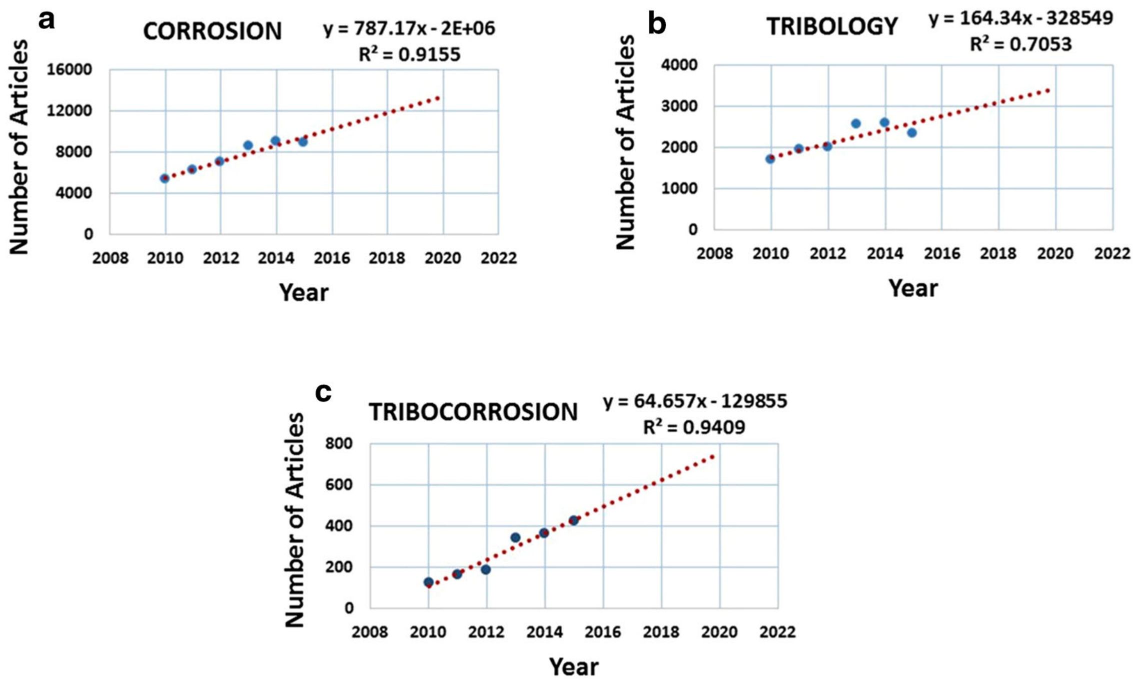


**Fig. 6** Projected growth of research for next 5 years based on linear model: (**a**) corrosion, (**b**) tribology, and (**c**) tribocorrosion

published per time period remained relatively low and constant for all databases. However, after 1970, the number of articles published for each time period seems to have been increasing exponentially. At present, the number of articles being published on the topic of tribocorrosion is greater than ever before. Even in the time period from 2010 to January 9, 2016, a greater number of articles have been published than the ten years prior (Fig. 6). Some articles might be missing due to the lack of digitalization of articles before 1960.

The number of articles over the years has been steadily increasing, as shown in Fig. 6 a–c. From 2010 to 2013, an increase in research in this area is observed due to the implant recalls of the DePuy Articular Surface Replacement, which had an anticipated failure rate of 49 % at six years [48–51]. In 2011, the U.S. Food and Drug Administration (USFDA) ordered manufacturers of MoM implants to conduct postmarket surveillance, increasing the number of articles covering a range of topics in medical implants [49]. However, from 2013 to 2014, the number of articles published has shown little growth. From the years 2014 to 2015, the number of articles actually seems to decrease. This trend could be due to issues arising from the recall of implant materials, particularly in relation to MoM implants, and for the increased research in the regenerative medicine field, with the usage of biological scaffolds [52].

If the decrease in published articles from the year 2014 to 2015 is an anomaly, the models for each implant based on the linear regression of the years 2010 to 2015 should be able to predict the growth of the research in these areas for the next three years, as shown in Fig. 6a–c. The articles published per year for each field over the last ten years show the growth of the different types of tribocorrosion approaches, as seen in Fig. 6c. The number of articles published per year on tribology-only and corrosion-only approaches has been steady with a slight decrease for the year 2015. However, the growth for articles published per year for the integrated approach with tribocorrosion has shown far greater growth than articles on single approaches (Figs. 1–6). These findings directly correlate with the importance of tribocorrosion in the current scenario. Moreover based on the reports on tribocorrosion, current focus is more on the development of new technologies to modify the surface for the improvement of longevity through reduction in the factors affecting tribocorrosion [53, 54]. In addition, the development of effective sensor technologies to detect the metal ions/wear particles from patients' blood is another area to be focused in the tribocorrosion research [55]. To examine the tribocorrosion issues in the in vivo exposure, effective animal models are to be developed through innovative potentiostat (microchip), which are miniature in size with biocompatible characteristics. The difficulties of data collections are to be solved with modern wireless technologies.

## 4 Conclusions

In this study, a short review of trend in the published papers in the area of corrosion, tribology, and tribocorrosion has been reported. The findings on the progress in the tribocorrosion research in the biomedical implants indicate that such research outputs have been rapidly increasing over the years. This can be associated to the need for more biocompatible and durable implants due to increased life expectancy in the aging population. If this trend continues, the number of articles published per year will continue to increase as biomedical science seeks to re-engineer articulating joints and dental implants and surfaces subject to corrosion and tribocorrosion.

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