Summer 9-30-2020

A Bibliometric Analysis of Research Productivity on Diabetes Modeling and Artificial Pancreas 2001 to 2020

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Abstract.

The prevalence of diabetes apparently increases all over the world. Thus, significant research works have been carried out in all aspects of the disease to control and mitigate its effects. Many researchers looked to the disease as a biomedical control engineering problem where the main task is identifying the model that can be used to mimic the healthy person's metabolism and therefore relieving the lives of millions of diabetics. This work aims to explore the dynamics of the produced scientific research in the area of diabetes modeling and control from a bibliometric method. In this work, a comprehensive bibliometric analysis of published research is carried out to give a guide to scientists in the field to explore research productivity and highlight the trends and tendencies besides showing the gaps for future research. The data were extracted from Scopus, a largest indexing and abstracting database of scientific literature. The analysis showed the field's leading countries, institutes, journals, articles, authorships, keywords, collaboration research networks, leading scholars, and a three-factor analysis of leading countries, institutions, and keywords.

Keywords: Diabetes, modeling, control, artificial pancreas, glucose-insulin dynamics, bibliometric

Introduction

Diabetes or Diabetes Mellitus (DM) as known in many literature resources is a chronic metabolic disorder characterized by prolonged elevated levels of blood glucose (National Diabetes Data Group, 1979; Organization, 1999; World Health Organization, 2006). This may be caused by the complete or partial failure of the insulin secretion - absorption mechanism. The most known types of DM are Insulin Dependent IDDM (Type-1) and Insulin Independent IIDM (Type-2) citation required. In type-1 DM, the pancreas usually did not provide insulin in response to glucose elevation, and patients with this type of diabetes must take insulin injections to control blood sugar values within the normal range. In Type-2 Diabetes, the pancreas still makes insulin, but not in enough amounts, with body resistance to the made insulin. The treatment here is a combination of diet, exercise, and sometimes, a diabetes medication.

The global prevalence of DM among adults over 18 years of age has risen from 4.7% in 1980 to 8.5% in 2014 The Emerging Risk Factors Collaboration (2010) and rising more rapidly in the middle- and low-income countries. According to WHO estimations, there are more than 425 million diabetics around the world, and by 2045, projections show this number rising to some 629 million diabetics globally (Elflein, 2020). WHO statistics show also that DM is one of the leading causes of death worldwide with almost 4 million deaths each year.

Management of DM mainly focuses on Controlling blood sugar (glucose) levels, glycemic control, by keeping blood sugar in a close-to-normal range and to minimize the frequency and severity of glycemic excursions. This can lead to the prevention or at least delaying the complications associated with DM. To reach the desired satisfactory glycemic control, there are many measures of performance; the most common in this regard is hemoglobin A1c (HbA1c) that assess long-term glycemic control. This is due to its clear relationship to the developed complications and episodes of hypoglycemia(Maahs et al., 2016). But A1c shows only the average glycemia and does not reveal information on the frequency or severity of hypoglycemic episodes.

Diabetes is one of the most studied biological systems by modern science from different perspectives and by different disciplines. Moreover, the complexity of the problem motivated the use of interdisciplinary-based approaches and methodologies with one goal to explore, understand the nature of the illness to manage it, and its associated consequences.

The Control of DM depends mainly on exploring the dynamics of glucose-insulin interaction within the normal healthy person compared to that of a patient suffering from this or that type of diabetes. The dynamics are complex as it connects many factors and many phenomena across many metabolic processes. A large group of mathematical models of about all kinds was suggested to describe the DM dynamics in order to explore its nature and consequently open the road to manage DM or in simple words to mimic the healthy person behavior.

The efforts exerted to find the secret formula of DM ranged from simple models with a few numbers of variables and parameters to more sophisticated multi variable multi-parameter models(Parker et al., 1999). From an engineering point of view, the research was to make some alternative closed control loop to the broken loop due to the failure of the pancreas. The early works of many researchers was concentrated on artificial pancreas(Albisser et al., 1974), while later work made the focus on the use of wireless communication achievements to close the loop with adequate sensor- transducer in the feedback of the system's control loop(Klonoff et al., 2011). Furthermore, there are many innovative advanced approaches to constructing computationally intelligent systems that has just

come into the limelight. These intelligent systems are supposed to possess human like expertise within a specific domain, adapt themselves, learn to do better in changing environments, and explain how they make decisions or take actions. These approaches include but not restricted to machine, and deep learning, artificial neural networks, expert, fuzzy logic, and smart systems. These methods are finding more and more applicability in all disciplines including biomedicine because of advances in computing capabilities, methods, and satisfactory results reached in many areas of science and life.

On the other side, research and commercial development of the artificial pancreas (AP) as one of the most popular in diabetes research, continue to progress rapidly. The AP promises to become a part of clinical care AP based clinical protocols and solutions(Maahs et al., 2016). One of the proposed research works(Kowalski, 2015) suggests a set of outcome measures of AP including continuous glucose monitoring CGM, time response characteristics such as time spent in in hypo- and hyperglycemia, in addition to glucose variability, safety measures, and technical metrics to evaluate AP system performance.

This paper aims to explore the overall picture of the published literature in the area by drawing a bibliometric analysis, identifying key pattersn and evaluating their results. Bibliometric studies play a pivotal role in viewing the trends and directions of research yielding, mostly, indicators of scientific performance(Raan, 2014). In the field of medicine and health sciences research. the bibliometric analysis shows a landscape map of publications along the time interval covered and could be a step toward other types of publications assessment either from qualitative or quantitative point of view. While there are a plenty of studies and research about diabetes mellitus from medical, clinical, and, engineering perspectives, the bibliometric studies related to such topics like Artificial Pancreas (AP) and closed loop insulin delivery system are more generalized studies without specific focus on topics like AP and related areas. One of recent studies(Fatehi et al., 2018) considers the applications and solutions of DM problems from pure technical side discussing different ICT achievements starting from using telephone calls in managing diabetes, mobile applications, social media, and Electronic Health Records (EHR). These studies can be considered a more review articles than a bibliometrics. Meanwhile, there are some bibliometric studies that either limited in the scope, countries and regions, or period they cover(Krishnamoorthy et al., 2009; Sweileh et al., 2014) . The period covered in the work from Krishnamoorthy 13 is from 1995 until 2004 with a scope about diabetes in general, while(Sweileh et al., 2014) covers a wider span from 1996 till 2012 but with publications limited to Arab countries region specifically. This work is a step to fill the gap in the bibliometric studies about AP covering the period from 2000 to 2020.

Research Questions

1. What are publishing trends in diabetes modeling and artificial pancreas from 2001-2020?
2. What are the preferred journals of researchers in diabetes modeling and artificial pancreas?
3. What are most productive authors, institutes, and countries in diabetes modeling and artificial pancreas?
4. What are authorship and collaboration patterns of research in diabetes modeling and artificial pancreas?
5. What are frequently used keywords in diabetes modeling and artificial pancreas?

Methodology

Bibliometric analysis was carried out to identify the research productivity of diabetes modeling and artificial pancreas in the world. Scopus database was selected as it is one of the largest and core

bibliometric databases of peer reviewed scientific literature. Scopus was used at Imam Abdulrahman Bin Faisal University (IAU), Dammam, Saudi Arabia on June 13, 2020. In the search box, following query has been run in title and keyword field. ("diabetes" OR type 1 diabetes) OR "insulin delivery system" AND (closed-loop AND biomedical AND systems OR "model predictive control" OR "artificial pancreas" OR "glucose feedback control system" OR "glucose sensor" OR "diabetes dynamic models"). We excluded "Note, Editorial, Letter, Short Survey", types of document.

The total 826 records were downloaded and imported in MS excel format for further refining. Each record was checked one by one to ensure the transparency and validity of the data. The irrelevant (158) and duplicated (5) records were removed and finally 663 relevant records were considered for data analysis. These records contain 193 conference papers, 454 articles, 12 book chapters, and 4 books. The whole process was once again repeated to ensure the accuracy of the data. The data analysis was performed with MS Excel, RStudio (Biblioshiny model), ScientoPy and VOS-viewer software.

Data Analysis

Analysis of the overall growth trend

Figure 1 shows the year wise frequency of publications and citations published from 2001 to 2020. There were 663 documents published by 270 journals, written by 1685 authors, affiliated with 1717 institutions and 36 countries. These documents received 14319 citations published in 649 English and 14 other languages.

A year-wise publication trend between 2001 and 2020 is presented at Figure 1. It shows that 2001 was the starting year for research publication on Diabetes modeling. In this year, two publication received 115 citations. The trend shows that publication and citation have gradually increased. This area has greatly prosperous between the years 2014 to 2019. The years 2001-2013 were disappointing years as there were very less publications in those periods. The significant growth has been observed from 2015 to 2019. The years 2018 and 2019 were marvelous as in that year's total 186 research publications were produced. The year 2019 is excellent as in that year 102 publications produced. However, a maximum of 1815 citations appeared in 2009. Since 2010 and 2014 are the second and third highly cited years and received 1558 and 1538 citations, respectively.

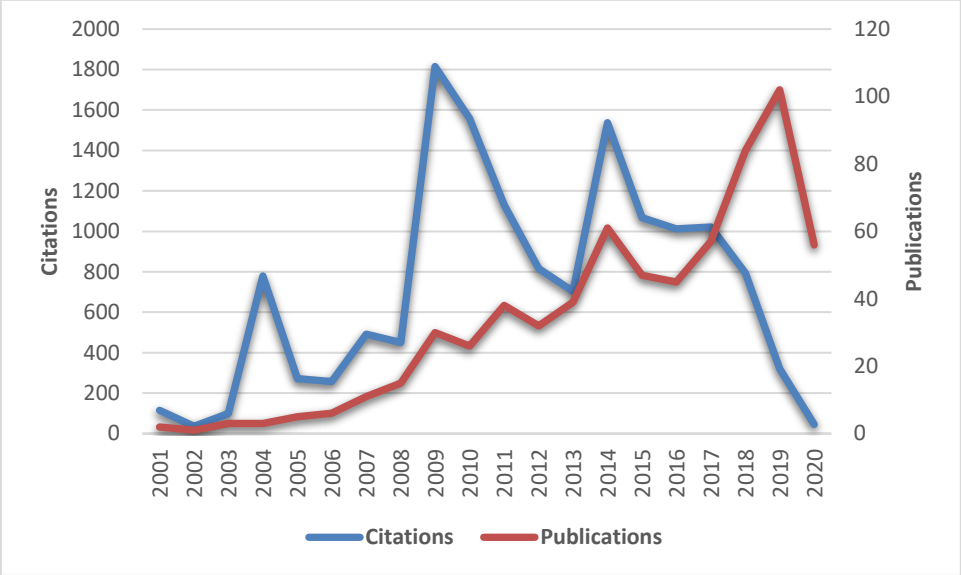


Figure 1: Publication and citation trend on diabetes modeling and artificial pancreas (2001-2020)

Highly Productive Countries

Three countries produced over 70 publications by each on diabetes modeling and control (table 1). The result shows that the USA is a top of the list with 244 publications and 9126 citations. The United Kingdom on 2nd rank with 80 publications and 3478 citations. Italy is on 3rd rank with 70 publications with 3643 citations; however, it received highest citation impact (52.04). Spain has produced 42 publications and received 389 citations, followed by the France with 35 publications and 1586 citations. Hungary and Denmark are on the bottom of the list, with 18 and 25 publications, respectively. However, citation impact comparison of top ten countries showed that Italy is on top of the list with 52.04 citation impact, followed by France and United Kingdom with each achieving 45.30 and 43.48 citations impact, respectively.

Table 1: Top 10 influential countries on Diabetes modeling and control

Rank	Country	TP	Percent	TC	Citation Impact
1	United States	244	36.9	9126	37.40
2	United Kingdom	80	12.1	3478	43.48
3	Italy	70	10.6	3643	52.04
4	Spain	42	6.4	389	9.26
5	France	35	5.3	1586	45.31
6	India	30	4.5	235	7.83

7	China	27	4.1	329	12.19
8	Canada	26	3.9	351	13.50
9	Denmark	25	3.8	226	9.04
10	Hungary	18	2.7	178	9.89

Influential Organizations

Top ten organizations producing research publications on diabetes modeling and control are given in table 2. Six organizations in the list belonged to the USA, two each from United Kingdom and Italy and one from Denmark. It shows that four key organizations have over 40 publications from which University of Padova, Italy, is on the top of the list with notable 51 publications, 3287 citations and 64.45 citation impact, followed by University of Virginia, USA, with 49 publications and 3332 citation impact, University of California, USA, with 43 publications, 2392 citations. Furthermore, it is noteworthy that University of Cambridge, UK (69.49) and University of Virginia, USA (68) have highest citation impact.

Table 2: Top Ten Highly Productive Organizations

Name of Organization	**TP**	**TC**	**Citations Impact**
University of Padova, Italy	51	3287	64.45
University of Virginia, USA	49	3332	68.00
University of California, USA	43	2392	55.63
University of Cambridge, UK	41	2849	69.49
University of Pavia, Italy	24	1622	67.58
SANSUM Diabetes Research Institute, USA	24	1324	55.17
Technical University of Denmark, Denmark	24	350	14.58
Illinois Institute of Technology, USA	21	362	17.24
Harvard University, USA	21	609	29.00
Imperial College London, UK	20	394	19.70

Most Prolific Authors

Table 3 highlights the top 10 most prolific authors on diabetes modeling and control, their first year of publication, their total publications, total citations and citation impact. The publications range of all the prominent authors are maximum 46 to minimum 18 articles. There are three authors that have over 39 publications (table 3). The list of most prolific authors shows that Cobelli C is the most productive authors with 49 publications, 3289 citations and 24 h- index, followed by Dassau E and Hovorka R with 39 publications each. It is noted that Haidar A and Jrgensen Jb are at bottom of this list with 18 publications each, similarly there is h-index is also among lowest in the form all the authors in this list. It is interesting to note that author Kovatchev B and Wilinska ranked 5th and 6th (based on TP) has highest citation impact among all authors in the list.

Table 3: Authors Impact

Author	TP	TC	First Year of Publication	h_index	Citation impact
Cobelli C	46	3279	2007	24	71
Dassau E	39	1776	2009	23	46
Hovorka R	39	2846	2004	24	73
Magni L	26	1732	2007	16	67
Kovatchev B	22	2050	2007	17	93
Wilinska Me	22	2026	2004	18	92
Cinar A	21	362	2008	9	17
Del Favero S	21	748	2011	11	36
Haidar A	18	400	2013	10	22
Jrgensen Jb	18	208	2010	8	12

Highly Influential Research Journals

The journals impact in respect of number of publications and citations including are highlighted in table 4. There are three journals that produced over 40 publications and eight impact factor journals in the top ten journals. It shows that the Journal of Diabetes Science and Technology is highly influential journal producing maximum 66 publications, 2713 citations. The Diabetes Technology and Therapeutics is on 2nd rank with 41 publications, 993 citations and good impact factor (4.49), followed by IFAC-Papers OnLine with 40 publications and 222 citations. Eight of the journals having impact factor in this list and half of them belong to Quartile 1. Majority of journals published by Elsevier and IEEE publishing groups. Five journals are publishing from United States

of America, two from United Kingdom, one from Netherlands, Ireland and Australia. Further, "Diabetes Care" has produced 16 publications and 1063 citations is the highest impact factor (15.27) among the top ten journals. The "Diabetic Medicine" is at bottom of the list and has produced 8 publications and received 172 citations.

Table 4: Key Journals

Title of Journal	TP	TC	IF	Q	Publisher	Country
Journal of Diabetes Science and Technology	66	2713	N/A	N/A	Diabetes Technology Society	USA
Diabetes Technology and Therapeutics	41	993	4.49	1	Mary Ann Liebert	USA
IFAC Proceedings Volumes (Renamed as IFAC-Papers online)	40	222	N/A	N/A	IFAC Secretariat	Austria
IEEE Transactions on Biomedical Engineering	20	750	4.49	1	IEEE	USA
Computer Methods and Programs in Biomedicine	17	294	3.42	1	Elsevier	Ireland
Diabetes Care	16	1063	15.27	1	American Diabetes Association	USA
Journal of Process Control	15	309	3.32	2	Elsevier	UK
Biomedical Signal Processing and Control	14	274	2.94	2	Elsevier	Netherlands
IEEE Journal of Biomedical and Health Informatics	9	148	4.21	1	IEEE	USA
Diabetic Medicine	8	172	3.10	2	Wiley-Blackwell	UK

Authorship Pattern

The authorship pattern highlights a minimum single author to a maximum of 90 authorship patterns on diabetes modeling and control research (Figure 2). The total 663 publications' analysis shows that the most used authorship pattern was three-authors as this pattern produced a maximum of 123 publications (19%), followed by four authors with 116 publications (18%), five-authors with 99 publications (15%). The authorship pattern of more than 10 has very limited publications as they collectively produced only 55 publications (8%).

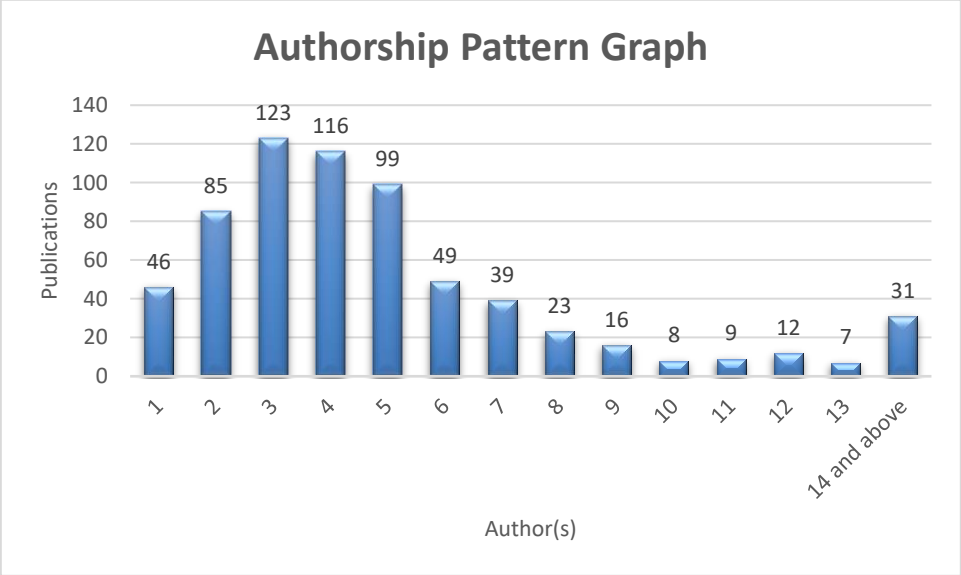


Figure 2: Authorship Pattern of Diabetes Modeling and Control

Author's Keyword analysis

Frequently used authors' keywords in diabetes research are highlighted in Figure 3. The keywords analysis has been performed in VOSviewer software. The minimum number of 10 keywords occurrence is selected and hence only 77 keywords meet the threshold out of total 1120 keywords. The distance and size of the bubble indicates the number of keyword occurrence and associational links. The top five keywords appeared more than 442 times. This keyword' artificial pancreas' is the most frequently and representative keyword as it appears 162 times followed by 'type 1 diabetes' that appear 134 times, 'diabetes' that appears in 80 publications, 'model predictive control' appears in 34 times and 'insulin' that appears 32 times. VOS has generated five clusters of these 25 keywords. Cluster-one (red) has 7 keywords including blood glucose, diabetes, glucose, hyperglycemia, insulin, simulation. Accordingly, other colors that are blue, orange, green and pink are also shown associational links (Figure 3).

Additionally, we also generated the most frequent keywords in last 7 years to observe the latest trends in diabetes research. The result presented at figure 4 shows that "artificial pancreas", type 1 diabetes, diabetes, type 1 diabetes mellitus, and model predictive control are the main keywords that are repeated most frequently in diabetes literature from 2014 to 2020.

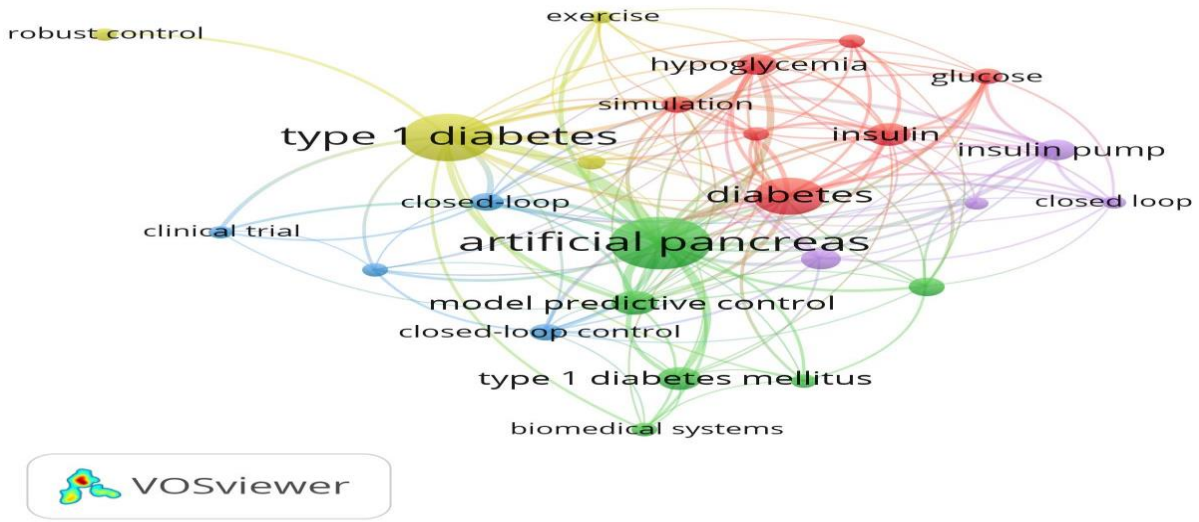


Figure 3: Frequently used keywords (2001-2020)

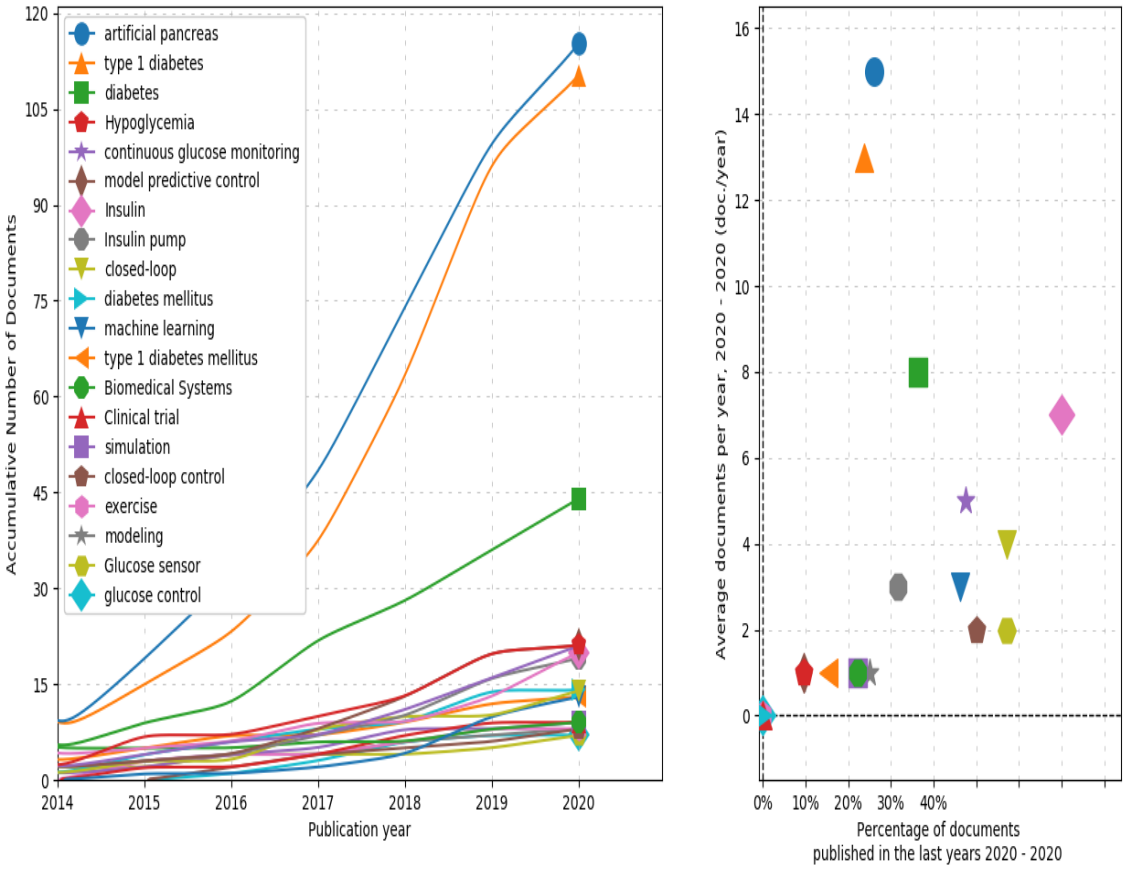
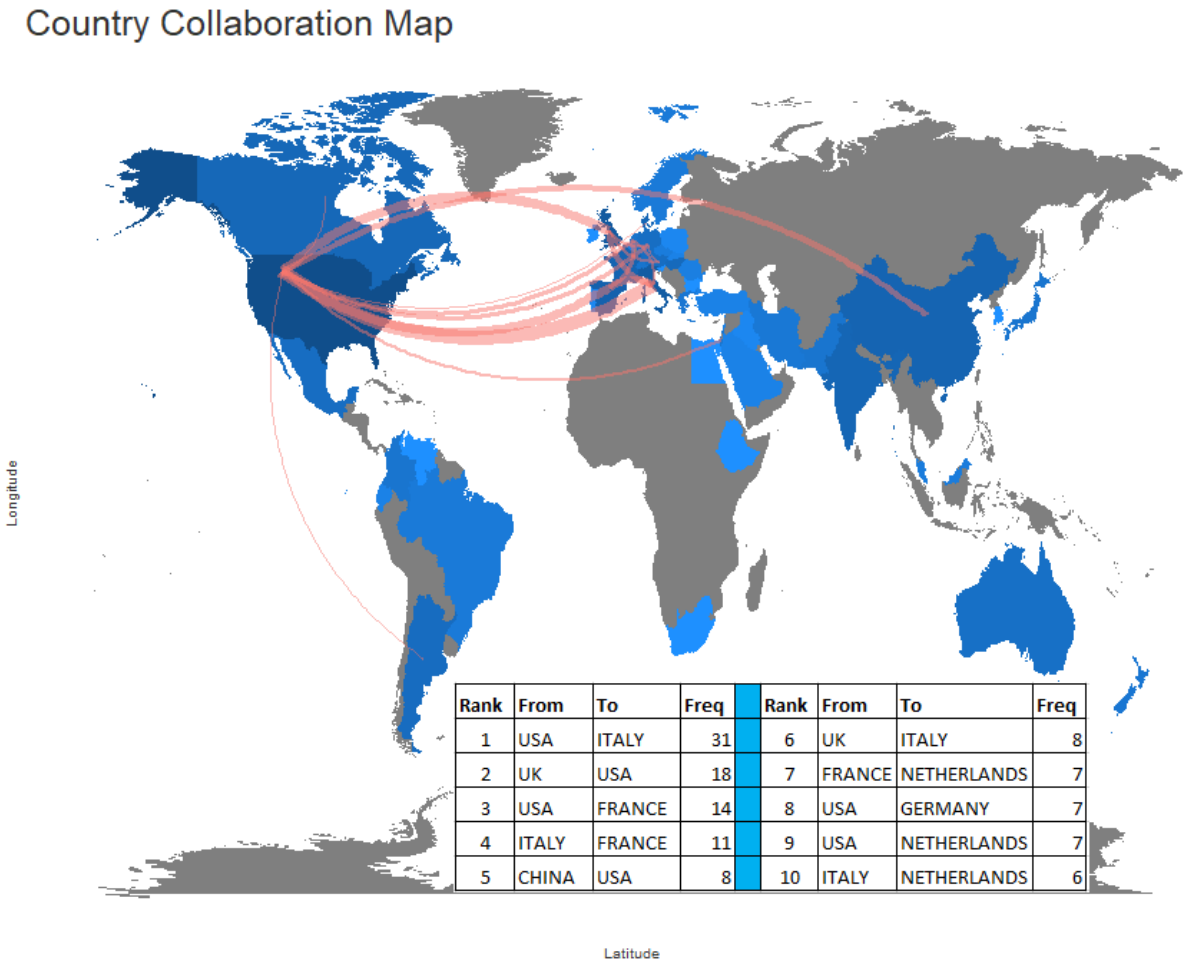


Figure 4: Author Keyword Analysis (2014-2020)

Country Collaboration Map on Diabetes Modeling and Control Research

Figure 5 shows the top 10 country collaboration map on Diabetes Modeling and Control research. The USA emerged a top collaborator with Italy (31 publications), United Kingdom (18 publications), France (14 publications), China (8 publications), followed by Italy with France (11 publications), United Kingdom with Italy (8 publications) and others. The least collaborator countries among 10 collaborators were Italy and Netherlands with six publications.



Rank	From	To	Freq	Rank	From	To	Freq
1	USA	ITALY	31	6	UK	ITALY	8
2	UK	USA	18	7	FRANCE	NETHERLANDS	7
3	USA	FRANCE	14	8	USA	GERMANY	7
4	ITALY	FRANCE	11	9	USA	NETHERLANDS	7
5	CHINA	USA	8	10	ITALY	NETHERLANDS	6

Figure 5: Country Collaboration Map

Three Factor Analysis (Keyword, Organization and Country)

The three-factor diagram has been generated of top 10 keywords, countries, and organizations on literature of Diabetes modeling and control. The size of the block shows the associational relationship with each factor. The top six keywords (artificial pancreas, type 1 diabetes, diabetes, insulin, insulin pump, hyperglycemia) have strong relation with top 10 countries (USA, UK. Italy, Canada, France, India, Spain, China, Denmark) Accordingly, other colors that are blue, orange, green and pink are also shown associational links with organization (University of Padova, University of Virginia,

Imperial College London, Illinois Institute of Technology, University of California, McGill university, university of Pavia, Oregon health and science university).

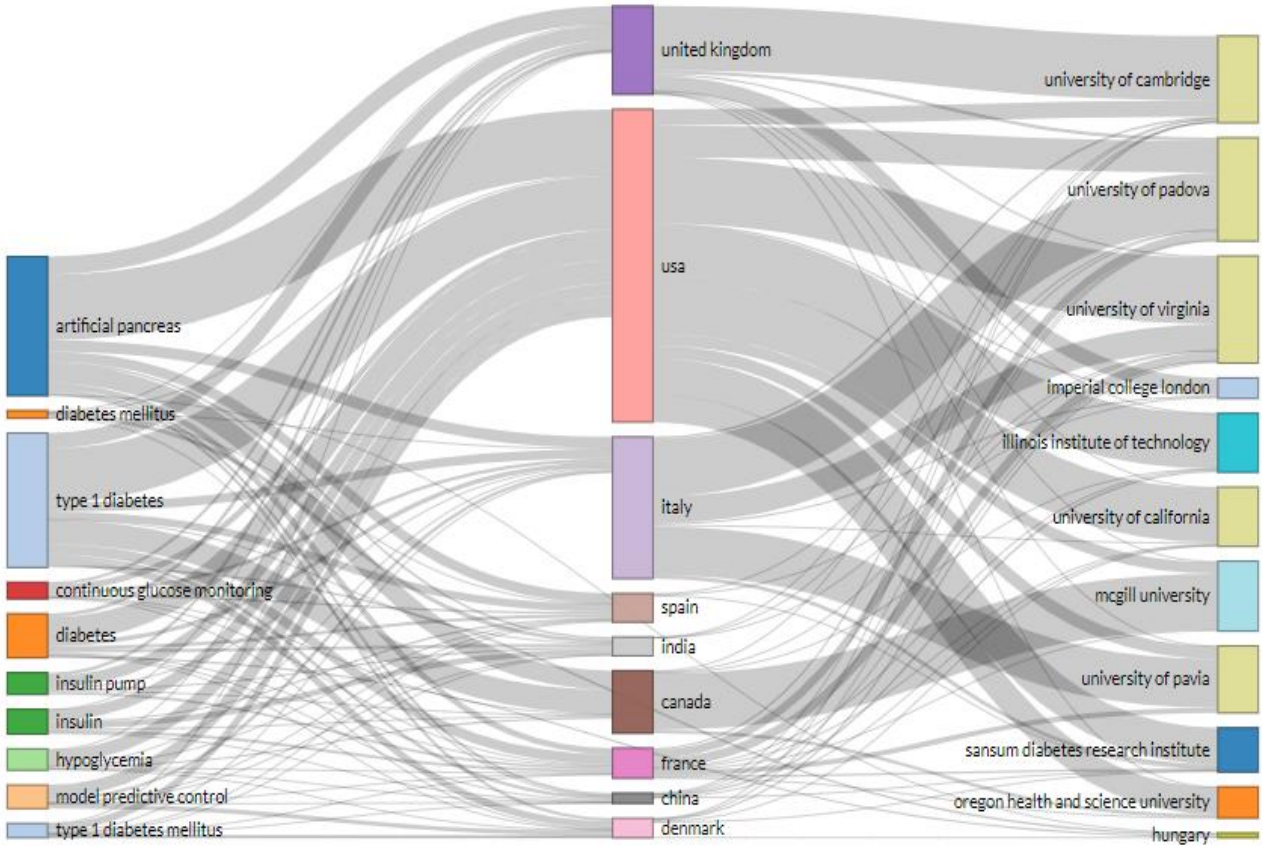


Figure 5: Three factor Analysis (Keywords, Country and organization)

Top Ten Highly Cited Articles

The bibliographic information of top ten most cited articles is indicated in table 5. There are seven articles in this list that received more than 308 citations. The publications years' range is between 2004 to 2015, and majority of the articles (seven) in this list are published after 2009.The article entitled "Nonlinear model predictive control of glucose concentration in subjects with type 1 diabetes" by Hovorka R published in 2004 in "Physiological Measurement" is on the top of the list with 755 citations, followed by article entitled "In silico preclinical trials: a proof of concept in closed-loop control of type 1 diabetes" by E Kovatchev BP in 2009 (Table 5). The article "Fully integrated artificial pancreas in type 1 diabetes: modular closed-loop glucose control maintains near normoglycemia" written by Breton M. is at the bottom of the list in top ten highly cited article.

Table 5: Highly Cited Articles

Title	Author	Affiliation	Source title	Year	TC
Nonlinear model predictive control of glucose concentration in subjects with type 1 diabetes	Hovorka R	University of Cambridge	Physiological Measurement	2004	755
In silico preclinical trials: a proof of concept in closed-loop control of type 1 diabetes	Kovatchev BP	University of Virginia	Journal of Diabetes Science and Technology	2009	477
Outpatient glycemic control with a bionic pancreas in type 1 diabetes	Russell SJ	Massachusetts General Hospital	New England Journal of Medicine	2014	369
Manual closed-loop insulin delivery in children and adolescents with type 1 diabetes: a phase 2 randomised crossover trial	Hovorka R	University of Cambridge	The Lancet	2010	363
Artificial pancreas: past, present, future	Cobelli C	University of Padova	Diabetes	2011	339
Diabetes: models, signals, and control	Cobelli C	University of Padova	IEEE Reviews in Biomedical Engineering	2009	319
A bihormonal closed-loop artificial pancreas for type 1 diabetes	El-Khatib FH	Boston University	Science Translational Medicine	2010	308
Microneedle-array patches loaded with hypoxia-sensitive vesicles provide fast glucose-responsive insulin delivery	Yu J	University of North Carolina At Chapel Hill	Proceedings of The National Academy of Sciences of The United States of America	2015	283
The uva/padova type 1 diabetes simulator: new features	Dalla Man C	University of Padova	Journal of Diabetes Science and Technology	2014	250
Fully integrated artificial pancreas in type 1 diabetes: modular closed-loop glucose control maintains near normoglycemia	Breton M	University of Virginia	Diabetes	2012	231

Discussion

The basic aim of this bibliometric study was to explore the research productivity of DM topic to get a deep insight about tendencies and trends of published scientific work related to the DM modeling and control. This work covers a period of 20 years and gives a more strong, realistic, reflective trends and analysis. Moreover, this study to the best of our knowledge, is the first detailed analysis of research productivity around diabetes modeling and control with 20 years coverage period. Figure 1 shows the trends of publications and citations in the field and the overall picture of published works shows a clearly exponentially increasing character that can be explained as the area of DM modeling and control had been become more and more attractive to researches from different backgrounds and the increasingly rate of diabetes prevalence in all countries. The last issue is clearly seen in the wide spectrum of journal and conferences that welcome research of such subject as shown in Table 4. The general trend of published articles indicates an increasingly behavior. This increase is in line with the overall increase in diabetes related biomedical publications(Shukla et al., 2020). Meanwhile, the increase in number of publications and research studies in biomedicine in general, and in diabetes related fields specifically, could be a result of the transformation caused by the obvious achievements in Information and Communication Technology(Fatehi et al., 2018) (ICT).These advancements made significant changes to science that allowed researchers to apply more sophisticated models to the modeling and control of closed loop control strategies and algorithms(Breton et al., 2012).

Regarding the leading countries in the field of DM modeling and AP, the picture is similar to that in many diabetes related bibliometric studies(Gao et al., 2017; Li et al., 2020) where about half of the publications were originated from USA, however, UK comes in the third or later place. Moreover, it can be noticed the absence of Germany in this list despite its pioneering research role in the field during the 1970s-1990s(Albisser et al., 1974). Moreover, the new competitors in list of leading countries of this research area are China, Hungary, Canada, Denmark, and India that indicate the more interest and emphasis on this research topic in various countries.

Looking to the leading research institutions that produced most of the articles, it is be noticed that these organization are of long history in this research field and they have high ranking scores in many fields. For instance, the University of Padova appears as one of the highly productive institutions in other bibliometric studies(Gaviria-Marin et al., 2018). In addition to the University of Padova's role in developing one of the most popular models and simulators in cooperation with the University of Virginia. The model /simulator has been used as a base in many research projects in and out of the university to mimic type T1DM clinical trials(Visentin et al., 2014). The two researchers with the highest number of publications belong to the pioneers of biomedicine and DM modeling and control. Specifically, the roots of research works performed by Cobili commenced in 1979, while Hovorka R first publication in this field started in 1991. Moreover, both authors, as seen from their profiles have collaboration in some publications and with many other researchers. Furthermore, it is noticed that the most cited publications are of 10 to 15 years back publication dates, that could be an indicator of their core-stone role in the progress of research in the field

The spectrum of journals and conferences that welcome research in DM modeling and control is wide and of high diversity. However, the journals with the highest number of publications are "Journal of Diabetes Science and Technology," "Diabetes Technology and Therapeutics," and IFAC-Papers online. The first two journals are more focused on diabetes and technology, while the third one is a Control engineering specialized journal that promotes the research in biomedical engineering through special issues about DM. In addition to that the three journals are publications of specialized societies related directly to the field of biomedicine and biomedical sciences.

The authorship pattern per article in the biomedical engineering field reflects the interdisciplinary character of the topics and subjects. The shown numbers of authorship patterns of 3-5 authors per article in most cases are similar to those in other disciplines like biotechnology(Singh, 2017) and health sciences(Haq, 2017).

Domain-specific keywords promote researchers to recognize the domain faster, easier, and efficiently and they can help in revealing the domain knowledge structure. The top 10 frequently occurred keywords show dominant words like "AP", "diabetes", and "type 1 diabetes" and this could indicate the authors' preference to select background disciplines keywords(Chen & Xiao, 2016). More generalized keywords make the search for articles easier that improves the chance for more citations. Meanwhile, the popularity of the term DM among researchers is becoming less and less common in most related publications.

The results related to the country collaboration demonstrate that the strongest collaborative is bilateral research work between USA and western European countries in the first place. This collaborative research relationship is seen in many other research disciplines like biomedical informatics and mobile health(Shen et al., 2018). The 2nd place in this regard goes to UK while China in the 5th.

The three-factor method of analysis provides a view of the multi-dimensional relationship patterns between countries, institutions, and keywords used establishing a research network. This way, the three classifications together gives the complementarity that can help go beyond simple statistics. Moreover, it provides a deeper insight of the evolution of a scientific research in the given subject(Banos et al., 2018).

The results of the provided analysis show clear dominant articles. The exploration of the article of the highest citations (Nonlinear model predictive control of glucose concentration in subjects with type 1 diabetes) shows its comprehensiveness and deep analysis to most methods of mathematical models obtained. Moreover, 2nd article in the citation classification is a collaborative research work between the diabetes modeling and control pioneers, Kovatchev BP, and Hovorka R which is in line with the collaboration map of the subject.

Limitations and Future Research Directions

This research work has few limitations. The bibliometric data of DM were extracted from Scopus database. The other databases such as Web of Science, PubMed may give additional insight about the research productivity in the field. Another limitation that can be considered because of the multidisciplinary and interdisciplinary character of the topic where the subject's terminology still not unified or agreed among researchers. The last fact could be a cause that some terms were not included in the search criterion. For example, the study focus is type 1 DM, while other types like type 2 DM were excluded from the scope of the work. From the other side, many articles in the field may be published in a wide range of journals and conferences and this might be a reason of excluding some of them in the work.

Although, there are many future works in the field to be done like expanding the included databases, other DM types, and the comparison between them. With the intent to develop more bibliometric analysis focusing on specific models and approaches like those proposed by University of Padova and University of Virginia or tracking the research output of the developed simulation models and their clinical analogy results. Another promising solution to the diabetes control problem that attract attention is the artificial intelligence-based models and their practicability.

Conclusion

For the period from 2001 to 2020, the research in the field of Artificial Pancreas, modeling, and control of diabetes as a subject category has not been analyzed bibliometrically yet. The obtained results have generated significant and new findings regarding the bibliometric dynamics of diabetes research. Specifically, the bibliometric analysis of DM modeling and control showed a constantly increasing trend of publications with clear peaks in 2014 and 2019. Moreover, the rate of citations increases rapidly around 2009 and 2014. The United States came in the first place and leads in terms of number of publication while Italy took the highest citation impact. From the other side, the American, British, and Italian universities are with nearly the same citation impact. The leading journals in area are two IEEE journals in biomedicine and health informatics. Kovatchev B, Wilinska Me, Hovorka R, and Cobilli C, are the pioneer researchers in the field. Additionally, the article with highest citations is Hovorka's article about model predictive control of DM of 2004. The evidence shown in the analysis provides more deep insights about the trends and tendencies of research work.

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