RESEARCH ARTICLE

Scientometric study of the effects of exposure to non-ionizing electromagnetic fields on fertility: A contribution to understanding the reasons of partial failure

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Abstract

The exposure to Non-Ionizing-Electromagnetic Fields (NI-EMFs) is often indicated as a cofactor responsible for the fertility reduction, which has been described in recent years. Despite the great interest in this topic and the research effort in exploring it, to date, there are no reliable data. Therefore, we carried out a scientometric analysis of the scientific literature published in peer reviewed Journals concerning this topic to better understand the reasons of this partial failure. To this aim, we identified and analysed 104 papers, published in last 26 years in peer-reviewed Journals, present in ISI Web of Knowledge Core Collection. Then, we analysed the impact of the Journals in which the papers were published as well as that of the single papers, the paper citation dynamics, the keywords citation bursts, the geographical localization of citations and the co-authorship dynamics of the Authors. As a result, we found that different animal models (rodent, rabbit, guinea pig, and swine) and different experimental approaches (epidemiological vs. experimental studies) have the same impact, highlighting the lack of universally adopted standard in research activity. The analysis of the temporal trend in keywords and the high differences in citations between the different countries (also in those belonging to the same geographical and socio-economical area) pointed out the difficulties in approaching this branch of study. Lastly, it was evident that the Authors did not behave as a connected community, but as unconnected clusters of very small size. In conclusion, based on the results of our analysis, we think that important efforts must be undertaken to adopt more standardized models and to improve the research quality and the information exchange within the scientific community, with the aim of improving the reliability and usefulness of the results of research regarding the effect of NI-EMFs on fertility.

Introduction

Important international Agencies claim that in recent years human fertility is decreasing in developed countries [1,2]. To date, there are not conclusive certainties about this phenomenon
and its causes are still obscure. During the years, different possible factors have been proposed to contribute to the accumulation of infertility risk factors. In particular, different conditions related to social changes have been taken into account as well as to lifestyle [3,4], such as tobacco [5–7] and marijuana smoking [8–10], alcohol [11,12], medication [13], caffeine [14], and the exposure to pesticides, solvents [15,16] and electromagnetic fields EMFs [17–19]. This last case, in particular, consists of electromagnetic waves characterized by frequency $f$, wavelength $\lambda$, and photon energy $E$. The frequency is inversely proportional to the wavelength and is directly proportional to the photon energy as described by Planck’s law:

$$E = \frac{hc}{\lambda}$$

where: $h = 6.62606896(33) \times 10^{-34} \text{J} \cdot \text{s} = 4.13566733(10) \times 10^{-15} \text{eV}$ is Planck’s constant.

The range of all possible frequencies is called “the electromagnetic spectrum” and ranges from 0Hz (static magnetic fields, SMFs), to $2.4 \times 10^{23} \text{Hz}$ ($\gamma$ rays). After billions of years of coexistence among biological organisms with EMFs of natural origin, in the last century the explosion of human technological activity has dramatically increased the presence in the biosphere of non ionizing radiations (NIR), i.e. EMFs whose energy is lower than the ionization energy of hydrogen (14 eV). In particular, the exposure to specific classes of NI-EMFs, such as static magnetic fields (SMFs), extremely low frequency electromagnetic fields (ELF-EMFs), radiofrequencies (RFs) and microwaves (MWs), had enormously increased.

SMFs are generated during the medical imaging procedures of Nuclear Magnetic Resonance Imaging (NMRI), when the patients are exposed for 30–60 min to three different EMFs: field gradients, radiofrequencies (RFs), and the static magnetic field (SMF). In particular, the SMF has intensities that usually range from 1–7 T, i.e. hundreds of thousands times stronger than those present in nature (the geomagnetic field on the Earth’s surface ranges from 25 to 65μT).

ELF-EMFs are defined as the electric and magnetic fields in the frequency range $>0$ to 100 kHz, the most important of which are of 50 and 60Hz, i.e. the frequencies generated by the production, transport and fruition of electricity in Europe and the USA, respectively.

RFs and MWs are used in Information and Communication Technology (ICT), for instance in cell phone, Wi-Fi, and Bluetooth protocols and in specific working condition (i.e. microwave welding).

Consequently, humans are continuously exposed to EMFs in public places, houses, schools, workplaces, and hospitals, thus originating in the public opinion and scientific community important concerns about their possible negative effects on health. To date, the International Agency for Research on Cancer, IARC, based on epidemiological and experimental, in vitro and in vivo studies, classified SMFs in group 3 (“not classifiable as to their carcinogenicity to humans”), while ELF-EMFs and RFs are classified as 2b (“possibly carcinogenic to humans”) [20]. As regards the possible toxic effect of EMFs on fertility unfortunately, the data now available, are not conclusive, thus it is impossible for scientists to offer the public opinion and decision-making organisms, reliable recommendations.

Here we carried out a scientometric analysis of the scientific literature, published in peer reviewed Journals, concerning this important issue with the aim of taking an updated picture of this branch of research. To this aim, in keeping with a validated approach already adopted by our [21] and other groups [22], we decided to carry out the quantitative assessment of several parameters known to be related with the scientometric evaluation of research activity. In particular, we analysed qualitative and quantitative parameters related to the papers and Journals that contain them, on experimental models and analytical approaches used, and on the authors’ co-authorship dynamics. We hope that the data we provide will be helpful to identify
a new strategy in planning future research activity and in improving the strength of research results.

**Materials and methods**

**Data collection**

As data source, we used the papers published between, January 1st, 1996 and May 31th, 2016 contained in Web of Science Core Collection (WoS) [23]. To select the paper used in this study, we used the Advanced Search Function of WoS, that uses field tags, Boolean operators, and query sets to create specific queries. For example, we used the following syntax:

\[ \text{TS} = (\text{topic } 1) \text{ AND } \text{TS} = (\text{topic } 2) \]

Where: TS is the topic

AND is the Boolean operator

In our queries, we used as topic 1 “fertility” combined with the following key words as topic 2: “Static Magnetic Fields”, “Electromagnetic Fields”, “Extremely Low-Frequency Electromagnetic Fields”, “Radiofrequency Electromagnetic Fields”, “Wi-Fi”, “Bluetooth”, “Microwave”.

We classified all the papers based on the biological model studied (human, rat, mouse, rabbit, guinea pig, swine), on the spectrum of EMF considered (SMF, ELF, RF) and on the experimental approach (epidemiological studies, in vitro or in vivo experiments). We calculated the number of paper citations per year in order to measure publications impact, and we assessed the impact factor (IF) and the 5 year IF of each journal to measure journals impact. Since these values change along the years we used, were possible, the data referred to 2015 and to 2015–2011 period, respectively. Otherwise, we used the most recent available data.

**Analysis of ISI key words and geographic distribution of EMFs papers citations**

The data related to the selected papers were processed for temporal and geospatial analysis by Sci² Tool (Sci² Team)[24]. We generated a temporal visualization of the burst of ISI keywords used in the papers, and a choropleth map that shows the geographic distribution of the selected papers distinguished by shades of colour for each Country, proportional to the number of citations.

**Map of science**

To explore the closeness of scientific disciplines related to the study of the effect of EMFs on fertility we realized, by using Sci² software, a map of science. It is a visual representation of a network of 554 subdisciplines (represented as nodes), that are aggregated to 13 main disciplines of science. Mapped subdisciplines are shown by size, related to numbers for journals and colours for disciplines.

**Co-authorship network**

To study the co-authorship dynamics of the Authors, we used an approach based on social networks, representing them as nodes of a network and, when two or more authors share a publication, they are linked by an edge. The open-source software Cytoscape 2.8.3 [25] has been, for network creation, visualization and analysis, carried out considering the networks as undirected. To study the topology of the networks obtained, in keeping with a previous work [21], we automatically computed the main topological parameters listed above, using:
**Number of nodes:** It is the total number of Authors involved.

**Number of edges:** It is the total number of interactions found.

**Connected Components:** It is the number of networks in which any two vertices are connected to each other by links, and which is connected to no additional vertices in the network.

**Clustering coefficient:** It is calculated as $CI = \frac{2nI}{kI(kI-1)}$, where $nI$ is the number of links connecting the $kI$ neighbours of node I to each other. It is the measure of how the nodes tend to create clusters.

**Network diameter:** It is the longest of all the calculated shortest paths in a network.

**Characteristic path length:** It is the expected distance between two connected nodes.

**Averaged number of neighbours:** It is the mean number of connections of each node.

**Node degree:** It is the number of interactions for each node.

**Node degree distribution:** It represents the probability that a selected node has k links.

**γ:** It is the exponent of node degree equation.

**$R^2$:** It is the coefficient of determination of node degree vs. number of nodes, on logarithmized data.

The statistical analysis of network organization (the so called “topology”) was used to take some inferences about the pattern of social behavior of Authors.

**Data analysis**

All the bibliometric and citational data related to the selected papers were checked for normality using the D’Agostino and Pearson normality tests. As they are not parametrical, we used the appropriate descriptive and inferential techniques, such as the Kruskal-Wallis or Mann-Whithey test depending on the needs, and the data are shown as median (25th percentile–75th percentile).

**Results and discussion**

It has been suggested that the exposure of humans to non-ionizing electromagnetic fields could be a contributory cause of the decrease in fertility. Here, we conducted a scientometric analysis of the literature concerning this topic, with the aim of taking an updated picture of the scientific production and of its impact on the scientific community. In addition, we studied the co-authorship dynamics of the authors involved in this field.

As first, we have found that the number of papers available on Web of Science Core Collection is relatively low. We found 107 papers concerning the effects of NI-EMFs on mammalian fertility. Since three of them have been discarded (two are referred to a non-mammalian model, D. Melanogaster, and the third has been retired), for the further analysis we considered 104 papers (see Table 1).

The first part of our study was aimed to assess the impact of different animal models, experimental approaches (epidemiological study, in vitro or in vivo experiments), and classes of EMFs in research activity. As indicators, we used the number of papers published and the number of citations per year of each paper [21]. We found that the overall distribution of this parameter was represented by the following equation: $y = 208.2 x^{1.869}$ ($R^2 = 0.9011$) which is in agreement with Bradford’s Law [26]. About one third of the papers are referred to humans (35/104), while the most used animal model is rat (44.2%; 46/104) followed by mouse (13.5%;
Table 1. List of selected papers.

| WOS Accession Number | Experimental Approach | Biological Model | Year of Publication | Citations per Year | IF 5 years IF |
|-----------------------|------------------------|------------------|---------------------|-------------------|-------------|
| **STATIC MAGNETIC FIELDS—SMFs** |
| A1996VX74000020       | Experimental mouse     | 1996             | 1.150               | 8.443             | 9.098       |
| 000084818100004       | Experimental mouse     | 2000             | 1.188               | 1.583             | 1.788       |
| A1994QF41100007       | Experimental rat       | 1994             | 3.727               | 2.141 (2004)      |             |
| 000327353100011       | Experimental swine     | 2013             | 0.000               | 1.208             | 1.162       |
| 0000753242000059      | Epidemiological human  | 1998             | 0.333               | 4.621             | 4.635       |
| **EXTREMELY LOW FREQUENCY ELECTROMAGNETIC FIELDS—ELF EMFs** |
| 000173700900009       | Experimental mouse     | 2002             | 2.929               | 1.583             | 1.788       |
| 000220310000005       | Experimental mouse     | 2004             | 5.583               | 2.644             | 2.579       |
| 000267594400007       | Experimental mouse     | 2009             | 0.714               | 0.188             | 0.342       |
| 000262310600009       | Experimental mouse     | 2009             | 0.000               | 1.583             | 1.788       |
| 000279430400007       | Experimental mouse     | 2010             | 1.000               | 1.208             | 1.162       |
| 000296459500006       | Experimental mouse     | 2011             | 1.400               | 1.208             | 1.162       |
| 000329505400003       | Experimental mouse     | 2014             | 2.000               | 1.583             | 1.788       |
| 000341343800006       | Experimental mouse     | 2014             | 0.500               | 1.165             | 1.265       |
| 0003620486000015      | Experimental mouse     | 2015             | 0.000               | 1.275             | 1.339       |
| 000169580200007       | Experimental rat        | 2001             | 3.267               | 1.583             | 1.788       |
| 000230823300010       | Experimental rat        | 2005             | 2.727               | 2.644             | 2.579       |
| 000234773500007       | Experimental rat        | 2006             | 4.400               | 1.583             | 1.788       |
| 000256627200006       | Experimental rat        | 2008             | 1.500               | 1.208             | 1.162       |
| 000265656700002       | Experimental rat        | 2009             | 0.000               | 1.603             | 1.369       |
| 000267633500001       | Experimental rat        | 2009             | 1.000               | 1.688             | 1.786       |
| 000270194600007       | Experimental rat        | 2009             | 1.000               | 1.688             | 1.786       |
| 0003574314000014      | Experimental rat        | 2010             | 0.500               | 1.441             | 1.474       |
| 000290290800004       | Experimental rat        | 2011             | 3.400               | 2.722             | 2.848       |
| 000303760700004       | Experimental rat        | 2011             | 0.000               | 0.839 (2011)      | 0.875       |
| 000299632500005       | Experimental rat        | 2012             | 1.750               | 2.722             | 2.848       |
| 000329867500007       | Experimental rat        | 2013             | 0.000               | 1.779             | 1.933       |
| 000327607800006       | Experimental rat        | 2014             | 3.000               | 1.583             | 1.788       |
| 000335765200007       | Experimental rat        | 2014             | 0.500               | 1.208             | 1.162       |
| 000269931800013       | Experimental rabbit     | 2009             | 0.000               | 1.276             | 1.305       |
| 000277962000016       | Experimental swine      | 2010             | 3.000               | 1.838             | 2.056       |
| 000301415200008       | Experimental human      | 2011             | 0.000               | 0.366             | 0.532       |
| A1993MN54400002       | Epidemiological human   | 1993             | 2.217               | 2.85              | 3.401       |
| 000079213100006       | Epidemiological human   | 1999             | 1.294               | 3.745             | 3.49        |
| 000073892200004       | Review human            | 1998             | 2.333               | 5.261             | 5.956       |
| 0002461251000013      | Review human            | 2007             | 0.000               | 1.128             | 1.639       |
| 0002461251000014      | Review human            | 2007             | 0.000               | 1.128             | 1.639       |
| **RADIOFREQUENCIES—RFs** |
| 000239219600018       | Experimental Mouse      | 2006             | 3.800               | 2.85              | 3.401       |
| 000262187700009       | Experimental Mouse      | 2009             | 4.286               | 3.022             | 3.072       |
| 000334273900001       | Experimental Mouse      | 2014             | 1.500               | 2.949             | 3.167       |
| 000072701500004       | Experimental Rat        | 1998             | 0.667               | 0.31 (2003)       |             |
| 000229298500008       | Experimental Rat        | 2005             | 6.182               | 0.562             | 0.639       |
| 000250192800028       | Experimental Rat        | 2007             | 6.667               | 4.426             | 4.333       |
| 000251984000005       | Experimental Rat        | 2008             | 5.125               | 2.219             | 2.399       |
| 0002658891000020      | Experimental Rat        | 2009             | 0.286               | 0.365             | 0.359       |

(Continued)
Table 1. (Continued)

| WOS Accession Number | Experimental Approach | Biological Model | Year of Publication | Citations per Year | IF 5 years IF |
|-----------------------|-----------------------|------------------|---------------------|-------------------|---------------|
| 000267702000010       | experimental          | Rat              | 2009                | 8.714             | 1.328         |
| 000270200400007       | experimental          | Rat              | 2009                | 3.714             | 1.68          |
| 000283616000004       | experimental          | Rat              | 2010                | 2.500             | 0.562         |
| 000269705000005       | experimental          | Rat              | 2011                | 0.000             | 0.812         |
| 000288010900005       | experimental          | Rat              | 2011                | 0.000             | 4.426         |
| 000290227000013       | experimental          | Rat              | 2011                | 7.800             | 1.606         |
| 000290292700002       | experimental          | Rat              | 2011                | 1.400             | 0.343         |
| 000293863900007       | experimental          | Rat              | 2011                | 4.800             | 1.204         |
| 000294436800002       | experimental          | Rat              | 2011                | 0.000             | 1.328         |
| 000306849000078       | experimental          | Rat              | 2012                | 2.500             | 1.504         |
| 000307588400005       | experimental          | Rat              | 2012                | 1.500             | 1.208         |
| 000307588400006       | experimental          | Rat              | 2012                | 1.500             | 1.208         |
| 00031563800002        | experimental          | Rat              | 2013                | 1.667             | 1.779         |
| 000316037000001       | experimental          | Rat              | 2013                | 3.333             | 2.85          |
| 000317837600026       | experimental          | Rat              | 2013                | 3.667             | 1.17          |
| 000323612000014       | experimental          | Rat              | 2013                | 2.000             | 1.208         |
| 0003275691000022      | experimental          | Rat              | 2013                | 4.333             | 2.85          |
| 000330046300005       | experimental          | Rat              | 2013                | 0.333             | 0.971         |
| 000331338700024       | experimental          | Rat              | 2014                | 0.500             | 3.25          |
| 000335765200001       | experimental          | Rat              | 2014                | 2.000             | 1.208         |
| 000340868200025       | experimental          | Rat              | 2014                | 1.500             | 2.309         |
| 000329826600026       | experimental          | Rat              | 2015                | 2.000             | 0.539         |
| 0003338399500005      | experimental          | Rabbit           | 2015                | 0.000             | 1.275         |
| 000360029900007       | experimental          | Rat              | 2015                | 0.000             | 1.127         |
| 000289040800015       | experimental          | Rabbit           | 2009                | 0.000             | 0.372         |
| 000349768200005       | experimental          | Rabbit           | 2015                | 0.000             | 1.208         |
| 000361005400006       | experimental          | Guineapigs       | 2009                | 0.143             | 1.0           |
| 000268637600002       | experimental          | Human            | 2009                | 19.286            | 3.057         |
| 000270616100029       | experimental          | Human            | 2009                | 15.429            | 4.426         |
| 000289084100005       | experimental          | Human            | 2010                | 2.833             | 3.022         |
| 000286110000004       | experimental          | Human            | 2011                | 4.600             | 3.695         |
| 000298367600011       | experimental          | Human            | 2012                | 10.250            | 4.426         |
| 000323180300007       | experimental          | Human            | 2013                | 1.000             | 2.429         |
| 000231271000007       | Epidemiological       | Human            | 2005                | 5.091             | 3.057         |
| 000255254900009       | Epidemiological       | Human            | 2008                | 4.375             | 7.105         |
| 000256952300003       | Epidemiological       | Human            | 2008                | 1.500             | 1.583         |
| 000295174100005       | Epidemiological       | Human            | 2011                | 5.400             | 1.441         |
| 000296935100014       | Epidemiological       | Human            | 2011                | 1.000             | 2.85          |
| 000357481700007       | Epidemiological       | Human            | 2015                | 0.000             | 1.214         |
| 000360655700014       | Epidemiological       | Human            | 2015                | 0.000             | 2.796         |
| 000182310000001       | Review                | Human            | 2003                | 6.769             | 1.057         |
| 000234832700002       | Review                | Human            | 2006                | 2.500             | 0.891         |
| 000246296500013       | Review                | Human            | 2007                | 0.222             | 0.891         |
| 000247917700025       | Review                | Human            | 2007                | 8.444             | 0.895         |
| 000254304100001       | Review                | Human            | 2008                | 6.500             | 3.98          |
| 000262709100021       | Review                | Human            | 2009                | 3.143             | 2.796         |
| 000268794800001       | Review                | Human            | 2009                | 2.429             | 1.165         |

(Continued)
14/104), rabbit (2.9%; 3/104), swine (1.9%; 2/104), and guinea pig (1%; 1/104). In our opinion, this finding is very interesting because it highlights that the most used animal models are rodents and rabbits (60.6% of papers). In these animals, the exposure to EMFs necessarily interests the whole body (usually they are exposed directly within the cages), thus it is impossible to discriminate the real reproductive effects from possible neuro-endocrine interferences, which constitute an important limit in interpreting the experimental data. The adoption of large animal models could be useful to overcome this limit, indeed in this context, it is possible to realize the exposure of the reproductive system without affecting the other endocrine or nervous structures [27].

When comparing the papers for differences in term of citations per year, depending on the animal model, we did not find significant differences [human 2.4 (0.95–4.85); rat 1.8 (0.5–3.38); mouse 1.3 (0.78–2.68), rabbit 0; swine 1.5 (0.75–2.25); guinea pig (0.1 (0.1–0.1); p > 0.05, Kruskal-Wallis test].

As regard the EMF typology studied, we found that most of the papers were addressed to study the effects of RFs (58.7%; 61/104), followed by ELFs (29.8; 31/104) and SMFs (4; 3.8%). In 3 cases (2.9%) different classes of fields were analysed. The analysis of the number of citations per year confirms the higher interest in the study of RFs when compared to ELF [2.4 (0.7–4.8) vs. 1.0 (0–2.5) citations per year respectively, p<0.05, Mann-Whitney u test] and the relatively low impact of papers referred to SMFs [0.75 (0.23–1.2) citations per year].

This finding is justified by the increasing interest in the study of possible health effect of fields employed in ICT, whose exposure is exponentially increasing in recent years. Not surprisingly, the median age of papers is 5 years for those referred to RFs and 7 years for those referred to ELFs. Very interesting is the scarce number of papers on the effects of SMFs and their age (in median 17 years), which is in contrast the dramatic increase in the number of patients and workers exposed with different modalities to these fields.

Ultimately, most papers are experimental studies (70.9%; 73/104), 17.3% (18/104) are reviews and 12.5% (13/104) are epidemiological surveys. This finding is consistent with the idea that the use of animal models is essential in doing research in this field. In terms of citation per year, we did not find statistically significant difference among these different approaches [epidemiological studies 1.5 (0.9–4.3), experimental studies 1.5 (0.5–3.4), reviews 2.7 (1.17–5.48), p > 0.05, Kruskal-Wallis test].
We classified the Journals in which the papers had been published in four thematic areas: “Biophysics”, “Reproduction”, “Environmental/Occupational toxicology”, “Miscellaneous”. Each Journal was listed in one or more of these classes, and we carried out an analysis using the set theory. Most papers were published in “Reproduction” Journals (33) then, in “Environmental/occupational toxicology” (25), in “Biophysics” (1), and in “Miscellaneous” (8), as reported in Fig 1.

This finding is very important, because in studying the effect of EMFs on biological samples the correct methodological approach in design and realization of EMF source has a key role. These Journals, perhaps, in the peer-review process and in the editorial choice, give less guarantees of the correctness of these aspects, underlining the importance of the biological aspect of the problem compared to the physical and engineering set up. Unfortunately, there are no Journals specifically devoted to the study of biophysics in reproductive cells, thus it is very hard to bring together the expertise of different specialists, with potential detrimental effects on the quality of science.

To complete this analysis, we assessed quantitative and qualitative parameters for the Journals. A higher number of papers was published in Electromagnetic Biology and Medicine (11 papers, 10.4%), Bioelectromagnetics (8 papers, 7.5%), Reproductive Toxicology (6 papers, 5.7%) and Fertility and Sterility (4 papers, 3.8%). We assessed the IF and the 5 year IF of the Journals: conscious of the limits of these parameters[21,28] we intended them as indicators of Journal impact and not as indicator of Journal quality. In both cases, the frequency distribution followed an exponential law (IF: $y = 328.8x^{-2.519}$, $R^2 = 0.928$; 5 year IF: $y = 238.2x^{-2.256}$, $R^2 = 0.938$), as expected (see Fig 2).

Fig 1. Venn’s diagram showing the number of Journals listed in different thematic areas (“Reproduction”, “Biophysics”, “Environmental/occupational toxicology”, “Miscellaneous”).

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The values of 25th percentile, median, and 75th percentile were: IF 1.606 (1.041–2.796) and 5 year IF 1.788 (1.215–3.072), and the maximum and minimum were 0.188–8.443 and 0.342–9.098, respectively. Referring to 5 year IF (more stable than IF) the Journals with the highest value (over the 75th percentile) are mainly related to the Environmental/occupational toxicology (Environmental Health Perspectives 9.089; Environment International 6.604; European Journal of Epidemiology 6.434; Mutation Research-Reviews in Mutation Research 5.956; American Journal of Epidemiology 5.471; International Journal of Hygiene and Environmental Health 4.002; Toxicology 3.967; Occupational and Environmental Medicine 3.490). Following are those related to Reproduction (Human Reproduction 4.635; fertility and Sterility 4.333, International Journal of Andrology 3.265), finally those of general interest, classified as Miscellaneous (PLoS One 3.535; Free Radical Research 3.167). Journal of Magnetic Resonance Imaging (3.449) was classified in Biophysics and Reproductive Toxicology (3.401) is classified both in Environmental/occupational toxicology and in Reproduction. The number of citations per year wasn’t related either to the IF or to 5 year IF of the Journal in which the paper was published ($r = 0.301$ and $r = 0.302$, respectively) (Fig 3).

From this data analysis, it emerges that the Authors’ choice of Journal in terms of thematic area, the impact of Journals (IF and 5 year IF) and the impact of the single paper (measured in number of citations per year) does not respond to a well-defined pattern and it does not display an easily predictable behaviour. In our opinion, this makes the univocal fruition of research products more complex for readers and other scientists.
We analysed the ISI key words cited in the papers to identify the most important topics addressed, with particular regard to the time window in which they have been approached. As shown in Table 2, it is possible to identify a specific trend in the evolution of interests\[21\].

In the nineties of the last century, researchers attention was focused on the investigation of possible negative effects of exposure to video terminals, while more recently it has been directed towards studying the effects of exposure to mobile phone radiations. This finding highlights an interesting characteristic of the study of developing technology impact rapidly on human health. Sometimes the evolution of technologies is so fast that, on one hand, there is the risk that the answers regarding the effects of exposure to a specific EMF sources will arrive when the originating technology is obsolete, and, on the other hand, new technologies will rapidly diffuse before they are adequately studied. The key words referred to the molecular or physiological determinants of the interaction between EMFs and biological systems are focused on oxidative stress, DNA damage, and melatonin. All these topics are closely related to the reproductive activity and represent potential targets of EMFs. In particular, the first two are of great interest because of their involvement in a myriad of biochemical pathways. The generation of ROS and their interaction with lipids and nucleic acids are reported to be involved in several pathological conditions, such as varicocele \[29,30\], exposure to heavy metals \[31\], carbon nanotubes \[32\], environmental toxicants \[33\], tobacco smoke \[34,35\] or simply aging \[36\]. This strengthens the idea that EMFs are co-stressors also involved in multifactorial pathogenic processes, instead of the concept of their role in causing pathologies. In the light of this consideration, the study of risk factor accumulation becomes very important as well as that of environmental
pollution in general. It is very interesting, in addition, to note that the most of the biological events under study are related to male fertility, while on the side of female reproduction, only fetal development and spontaneous abortion have been considered by researchers. This could be due to the easier availability of male gametes, and to the difficulty in studying the effect of a cofactor in the context of female reproductive activity, which involves multi-organs and multi-system functions. This lack still represents a challenge for scientists involved in the study of EMF effects on health as well as on female fertility.

To study the contribution of different Countries and Geographical area on this kind of study, we carried out the georeferentiation of the citations of the examined. As a result, we found the data shown in Fig 4.

As it is evident, the developed Countries are characterized by a higher parameter, with the leadership of the USA and Europe. This datum is not per se surprising, but it provides the opportunity for two important considerations.

1. as seen in other scientific fields related to reproduction [21], several developing countries are excluded from research activity on such important issues. Here, it is interesting to note that China which is experiencing an amazing diffusion of technology and, consequently, exposure of humans to EMFs, seems to be scarcely active in research on possible negative consequences on fertility. On the contrary, India has a noticeable activity on this field.

2. Single European Countries display highly different behaviours. This is an interesting finding, because they have a similar technological development and are subjected to the same

### Table 2. List of citation bursts of ISI keywords in papers published in peer-reviewed Journals related to the effect of EMFs on fertility.

| Class            | ISI key word          | Weight | Start | End  |
|------------------|-----------------------|--------|-------|------|
| Generic keywords | fertility             | 2,718  | 2008  | 2009 |
|                  | exposure              | 2,535  | 2006  | 2007 |
|                  | in vitro              | 4,318  | 2011  | 2013 |
| Processes        | Lipid peroxidation    | 1,909  | 2012  | 2015 |
|                  | oxidative stress      | 2,237  | 2012  | 2016 |
|                  | Single strand         | 1,669  | 2005  | 2008 |
|                  | melatonin             | 1,765  | 2005  | 2007 |
| EMF source       | Magnetic field        | 1,684  | 2012  | 2013 |
|                  | video display terminals | 1,933 | 1992  | 1998 |
|                  | Microwave exposure    | 1,684  | 2012  | 2013 |
|                  | 60Hz                  | 1,651  | 2012  | 2016 |
|                  | Cellular phones       | 1,761  | 2012  | 2013 |
|                  | Mobile phone radiation| 1,782  | 2013  | 2016 |
|                  | Mobile phones         | 1,837  | 2011  | 2016 |
| Male fertility   | Semen quality         | 1,293  | 1996  | 2008 |
|                  | adult male            | 2,389  | 2008  | 2010 |
|                  | Male fertility        | 2,826  | 2010  | 2011 |
|                  | spermatogenesis       | 1,716  | 2012  | 2012 |
|                  | Human spermatozoa     | 1,193  | 2012  | 2016 |
|                  | Male infertility      | 4,476  | 2013  | 2016 |
| Female fertility | Fetal development      | 1,829  | 1998  | 2005 |
|                  | Spontaneous abortion  | 1,933  | 1992  | 1998 |

Class = phenomenon to which the keywords are referred. ISI keyword = keyword adopted by ISI system to classify the paper. Weight: intensity keyword of use of. Start = starting year of citation burst. End = end year of citation burst.

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sovre-natioonal policy of research funding. In the EU, the most important program for research funding is Horizon 2020. It is main as a top-down program, in which the priorities of funding have been a priori decided by the EU. Remarkably, here, the research funding on ICT has a central role, as stated by the EU, that claims that “ICT brings unique responses to society’s challenges such as the growing needs for sustainable healthcare and aging well, for better security and privacy, for a lower carbon economy and for intelligent transport”[37], but there are not specific funding lines for the study of effects of EMF on health. In addition, the research funding policy on reproduction and reproduction-related issues in the EU changes according to the country[21,38]. This is due to the different scientific and regulatory traditions among the European countries and to the different weight of involved stakeholders (public opinion, patients associations, companies, etc.).

The study of the reproductive effects of EMF exposure on fertility requires a multi-disciplinary approach, for this reason we set up a map representing the co-citation of the papers we identified to study the link among the different disciplines involved in this field (see Fig 5).

As it is evident, unfortunately, hard sciences and electrical engineering on one hand and the health professionals as well as the medical specialities on the other hand, are not so close as it would be desirable, with important difficulties in assuring high quality research and, consequently, reliability of the data with relative inferences.

Finally, to complete our analysis with the description of authors’ co-authorship dynamics, we set up and analysed co-authorship network (Co_AN) (Table 3 and Fig 6).

In the network, the Authors are represented as nodes and the co-authorship as a link. The analysis of network topology shows that a high number of small size (Main-Components-Co-Authorship Network)connected components (sub-networks) constitutes it: the larger one
accounts for about 5% of Co_AN. In addition, all the components are characterized by the tendency to form highly clustered structures that do not communicate with each other. These data suggest that the scientific community involved in the study of such important fields is highly fragmented; highlighting once again the lack of communication among the scientists involved in this such important field. This pattern is specific and different from the researcher network involved in strictly related fields, such as reproductive medicine [21,22], and denotes an important problem in assuring high quality research. Indeed, now it is clear that EMFs act as cofactors with other etiological agents and the related risk is near to the background. Thus we would need big collaborations and transnational networks of researchers to collect a sufficient amount of data [39], otherwise it will be impossible to answer the question on possible negative effects of EMFs on fertility and on health. Unfortunately, the community involved seems not to have reached an adequate critical mass.

Conclusions

The study of the possible effects of EMF exposure is an issue of continuously growing importance, in a modern technological society. The bibliometric analysis we carried out leads us to make interesting conclusions. In particular, it is evident that:

**Table 3. Results of co-authorship network topological analysis.**

| Parameter                  | Co_AN | MC1_Co_AN | MC2_Co_AN | MC3_Co_AN |
|----------------------------|-------|-----------|-----------|-----------|
| Number of nodes            | 452   | 23        | 16        | 15        |
| Number of edges            | 1339  | 124       | 36        | 65        |
| Connected components       | 74    | 1         | 1         | 1         |
| Clustering coefficient     | 0.953 | 0.909     | 0.819     | 0.941     |
| Diameter                   | 3     | 3         | 3         | 2         |
| Charact. path length       | 1.241 | 1.605     | 1.967     | 1.381     |
| Avg. number of neighbours  | 5.925 | 10.783    | 4.5       | 8.667     |
| γ                          | 0.163 | 0.110     | -1.112    |           |
| r                          | 0.004 | 0.112     | 0.403     |           |
| R²                         | 0.012 | 0.022     | 0.447     |           |

For the explanation of topological parameters, refer to the Materials and Methods section. Co_AN = Co-Authorship Network, MC1_Co_AN, 2, and 3 = Main-Component- Co-Authorship Network 1, 2 and 3, are the three larger subnetworks of Co_AN.
The scientific effort in studying this topic is very limited;

There are large differences in the research outcome among the different regions and countries, likely due to different research funding but, also, to the different cultural and scientific traditions;

It would be important to make a larger effort to increase communication among the different researchers involved, with a wide range of competences, from general medicine and assisted reproductive technology, to electrical and electronic engineering, computational dosimetry and the networking activity of Authors.

We think that analysis results could be very interesting for researchers and professionals involved in fertility study (physicians, andrologists, gynaecologists, biologists, embryologists, veterinarians), for clinicians, editors of scientific Journals, as well as editorial board members. In addition, this information could be of interest to officers of funding agencies and of

Fig 6. Co_AN. It is a visual representation of Co_AN, in which the Authors are represented as nodes and the co-authorships as links.

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policymaking organisms, as well as for all the people that are interested in carrying out a critical reflection on the effects of EMFs on human and animal health. Indeed, we are faced with new technologies (home automation, smart cities, self-driving cars) that will certainly determine an increase in human exposure to EMFs in the whole environment.

From our data, it is evident that, to obtain reliable information on this topic, it would be necessary to revise of research activity that would be more organized in terms of collaboration and information exchange, with the adoption of standardized models (cellular, animal and exposure parameters) and the realization of large size studies. Research funding could act as a catalyst, to reach these objectives. Unfortunately, to date, the most important programs for research funding, at least in the EU, do not seem to take this opportunity.

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