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# Methodological Research of High Entropy Alloys by Using Bibliometrics Analysis

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The novel alloys, which include five or more elements in almost equal or so near equal portions, are termed High entropy alloys (HEAs). Besides, this kind of alloy has a configurational entropy of more than 1.5R. HEA makes it a challenge to new properties and different structures, which give so many opportunities to research. This research offers a reliable overview of HEAs literature to predict the development and rate of technological pattern improvement. Also, it can be a great guide to beginner researchers in that field. It also introduces the most active institutes and academics to make collaborations with. Additionally, this research will allow industry policymakers to profit from SMA progress in many sectors. This work focused on the yearly advancement of HEAs publications and citations to deal with the general progress in HEA studies. Moreover, due to recognizing the intellectual foundations, this research categorized the publications, authors, institutes, countries, and journals based on their scientific efficiency from 2004 through 2020.

***Keywords:*** *High Entropy alloy (HEA), Bibliometrics analysis, Literature review, Scientific publications*

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## 1. Introduction

In the last two decades, the phenomena of alloying got a new challenge, High Entropy alloys (HEAs). HEAs are the new magic and novel alloys which consist of 5 or more elements in equimolar ratios or near equimolar ratios [1, 2], each element's ratio has to be in the range of 5 to 35 at. % [1-3]. Furthermore, a new sort of HEA has developed, known as the second generation, concerned with non- equimolar parts in a multiphase solid solution [4]. In addition, another definition for HEAs is also available based on entropy which is these alloys have a configurations entropy of more than 1.5 R when R is the gas constant [5]. Such a countless number of new compositions could be achieved and developed with those new phenomena of alloying, and it may give new properties, different properties. It leads to new phenomena as well [6, 7]. Hence, there is a sharp increase in publishing studies by metallurgic researchers and physicists in that field recently [3, 8-10].

An appropriate source for mapping scientific and technological domains is Bibliometric information, i.e. patents, science articles, and citations [11]. According to reports, bibliometric studies are susceptible techniques that can quantitatively measure research outcomes using geometrical and statistical methodologies [12]. Moreover, that approach could adequately examine the metrological properties of information produced in a particular field [13]. Furthermore, Bibliometrics greatly aid scholars by offering them a systematic approach to identifying the relevant institutions for the research and promoting upcoming

academic staff, thereby encouraging technical and scientific developments [14, 15].

The present study aims to collect and interpret the academic terrain of HEAs research on a worldwide scale using bibliometric analysis tools. Our primary objectives were to map and determine frontiers during the study period, assess trends in research, build networks for research collaborations, and examine the publication mode. Moreover, this research reviewing the scientific published studies in the period of 2004 to 2020. This work should count as a literature review study that listed some of the most cited articles and sources in the field of HEAs. This present study will investigate studies in the HEAs field, which contains different criteria such as publications, authors, institutes, countries, and journals. It also could be a great tool and guide for researchers to get informative and most acceptable sources in the field of HEAs.

## 2. Materials and Methods

The data which are presented in this study have been taken from an online database. Moreover, Science Citation Index Expanded (SCI-EXPANDED) and Conference Proceedings Citation Index-Science in Web of Science "v 5.35 Web of Science core collection basic search (WoSCC)", all data attracted from WoSCC that accessed by Firat University, Elazig, Turkey. These searches were customizing in the range of 2004 to 2020. Web of Science was used to cover and reach data because it is an excellent source for data citations. It is regularly used as a course resource for scientific publication analysis [16, 17]. In addition, it is an alive and daily updated database that could rely on. It gives many facilities in several categories, including publications, authors, institutes, countries, and journals. In this review, some keywords were used like High Entropy alloys (HEAs), Core effects, High Entropy effect, and High entropy alloy. These key searches helped to cover the maximum ratio of publications in the field of HEAs.

## 3. Results

This study, which includes all the publications from 2004 to 2020, in the scope of HEAs 6796 publications could be covered. A vast number of them are articles, including 222 review articles; besides that, 28 book chapters were dealing with HEAs which is such an excellent ratio of the whole publications. Most of these mentioned studies were written in English (6643 out of 6796); the other languages became minor compared to English written studies. The "*Entropy"* is the most frequent keyword with 5423 times used as a keyword in all HEAs publications. Other keywords also were used in common such as *"High entropy alloys"*, *"High entropy alloys"*, *"High entropy alloys"*, *"High entropy alloy"*, they are used 6738 times in HEA studies. In addition, the following sections give an overview of other categories, including publications, authors, institutes, countries, and journals of the HEAs field from 2004 to 2020.

Moreover, HEAs got much attention in recent decades from material science and metallurgical study communities because of unusual microstructural, flexible properties and compositions [3, 8-10]. As a result, the research effort is completely unrestricted [18]. The publication rates yearly in the field of HEAs between 2004 and 2020 showed in **Hata! Başvuru kaynağı bulunamadı.**. From the figure, we can understand that there is a gradual increase in the early years of studying in that field, but between 2012 and 2013 and after there is a significant rising ratio of research. Additionally, if we compare 2017 and 2018, the rate of published studies in 2018 is 1.5 times greater than in 2017. As far as we notice from the bar charts, we easily could see that huge difference between early years (e.g. 2004) and recent years (2020), the researches rate is like more than 45 times increased (from 38 in 2004 to 1833 in 2020). The highest ratio of published researches in 2020 is recognized as 27 % of the total number of studies in that time frame. Also, in 2021, it has been 997 publications till 14/6/2021, which means we can observe that dealing with HEAs is an increasingly interesting topic for researchers.

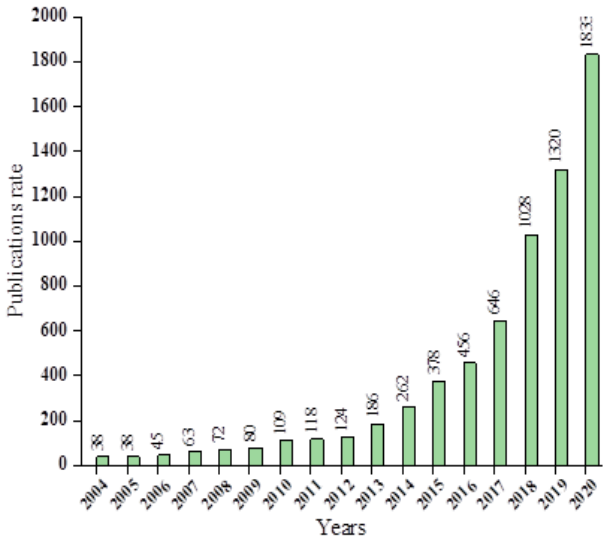


**Fig.1.** The progress of published articles in the HEAs field between 2004 and 2020

### *3.1 Covering fifteen most cited HEA researches*

In order to show the most frequently cited published studies in the field of HEAs, here we listed the top fifteen articles, as shown in

Table **1**. Although the accumulated citation is not a perfect indicator of an academic work's effect or value, it does give a marker of its acknowledgment within the research world

[19]. In addition, the most-cited articles might reveal how research fields have progressed [20]. It is noticeable from Table **1**, the most cited article from the beginning of HEAs research till now is an early article which was written by Yeh et al. in 2004 and titled "*Nanostructured high-entropy alloys with multiple principal elements: Novel alloy design concepts and outcomes*". It gives basic concepts for that new novel alloys. Besides, this article focused on using a new approach to design multi-element alloys with equimolar or near-equimolar portions. Yeh et al. mentioned that this new alloying concept could allow countless new alloys with different compositions. It also leads to new applications and new properties.

In addition, the second one is a review article titled *"Microstructures and properties of high-entropy alloys."* was published by Zhang et al. in 2014. It is such a great source in HEAs, and it contains 93 pages that cover so many headings in the field of HEAs like introduction, four core effects, Thermodynamics, Kinetics and alloy preparation, properties, modeling and simulations, future development, and research. Even though it is so new compared to the first listed in

Table **1**, it attracted so many researchers because it gives many concepts and scientific facts related to HEAs.

In 2017, Miracle and senkov published a review article in the HEAs field titled *"A critical review of high entropy alloys and related concepts"*. It covered so many topics in the area of HEAs, such as definitions, Thermodynamics of complex, concentrated alloys, microstructures, properties, etc. for that reason, it could get 2009 citations in 3 years, which is such a great result, and it gets the third order in Table **1**.

**Table 1.** Fifteen most often cited publications in the field of HEAs during the study time

| No | Title | Authors | Journal | Year | Times cited |
|---|---|---|---|---|---|
| 1 | Nanostructured high-entropy alloys with multiple principal elements: Novel alloy design concepts and outcomes | Yeh, JW; Chen, SK; Lin, SJ; et al. | Advanced engineering materials | May 2004 | 4123 |
| 2 | Microstructures and properties of high-entropy alloys | Zhang, Yong; Zuo, Ting Ting; Tang, Zhi; et al. | Progress in Materials Science | Apr 2014 | 2397 |
| 3 | A critical review of high entropy alloys and related concepts | Miracle, D. B.; Senkov, O. N. | Acta Materialia | Jan 2017 | 2009 |
| 4 | A fracture-resistant high-entropy alloy for cryogenic applications | Gludovatz, Bernd; Hohenwarter, Anton; Catoor, Dhiraj; et al. | Science | Sep 2014 | 1961 |
| 5 | Metastable high-entropy dual-phase alloys overcome the strength-ductility trade-off | Li, Zhiming; Pradeep, Konda Gokuldoss; Deng, Yun; et al. | Nature | Jun 2016 | 1183 |
| 6 | The influences of temperature and microstructure on the tensile properties of a CoCrFeMnNi high-entropy alloy | Otto, F.; Dlouhy, A.; Somsen, Ch.; et al. | Acta Materialia | Sep 2013 | 1178 |
| 7 | Solid-solution phase formation rules for multi-component alloys | Zhang, Yong; Zhou, Yun Jun; Lin, Jun Pin; et al. | Advanced Engineering Materials | Jun 2008 | 1047 |
| 8 | High-Entropy Alloys: A Critical Review | Tsai, Ming-Hung; Yeh, Jien-Wei | Materials Research Letters | Apr 2014 | 1024 |
| 9 | Mechanical properties of Nb25Mo25Ta25W25 and V20Nb20Mo20Ta20W20 refractory high entropy alloys | Senkov, O. N.; Wilks, G. B.; Scott, J. M.; et al. | Intermetallics | May 2011 | 970 |
| 10 | Refractory high-entropy alloys | Senkov, O. N.; Wilks, G. B.; Miracle, D. B.; et al. | Intermetallics | Sep 2010 | 890 |
| 11 | Prediction of high-entropy stabilized solid-solution in multi-component alloys | Yang, X.; Zhang, Y. | Materials Chemistry and Physics | Feb 2012 | 809 |
| 12 | Effect of valence electron concentration on stability of fcc or bcc phase in high entropy alloys | Guo, Sheng; Ng, Chun; Lu, Jian; et al. | Journal of Applied Physics | May 2011 | 785 |
| 13 | Sluggish diffusion in Co-Cr-Fe-Mn-Ni high-entropy alloys | Tsai, K. -Y.; Tsai, M. -H.; Yeh, J. -W. | Acta Materialia | Aug 2013 | 778 |
| 14 | Phase stability in high entropy alloys: Formation of solid-solution phase or amorphous phase | Guo, Sheng; Liu, C. T. | Progress in natural science-materials international | Dec 2011 | 752 |
| 15 | Recent progress in high-entropy alloys | Yeh, Jien-Wei | Annales de chimie-science des materiaux | Dec 2006 | 706 |

*3.2 Reviewing top fifteen Journals*

Based on data collected in this research, it has covered 2939 researches published by these top 15 journals, which means

43.25% of the total publications in HEAs. According to decreasing publications in HEAs from 2004 till 2020, the top 15 sources have been listed in
Table **2**. These fifteen journals could use as the most important and most excellent tools to study in the field of HEAs. *Journal of Alloys and Compounds* (Netherlands) has been found as a core journal with 677 published studies, and it became 9.96% out of total publications in the period of

Table **2**, which published 300 articles (4.4%). Since HEAs get much interest in the last decade (as can be noticed from

Table **2** gives 15 most HEA studies publisher journals.

our research. After that, the second source which deals with HEAs is *Materials Science and Engineering A Structural Materials Properties Microstructure and Processing* (Netherlands) published 368 studies (5.4%). Following these two sources, *Acta Materialia* (United Kingdom) could be found in the third row in
**Hata! Başvuru kaynağı bulunamadı.**), that's why recently, more journals adding HEAs to their topics to deal with and publishing articles in that field. Even though

**Table 2.** The top fifteen Journals which publishing studies in the HEAs field along study period

| No | Title of sources | Publications in that field | Country | Impact factor (2019) |
|---|---|---|---|---|
| 1 | Journal of Alloys and Compounds | 677 | Netherlands | 4.650 |
| 2 | Materials Science and Engineering A Structural Materials Properties Microstructure and Processing | 368 | Netherlands | 4.652 |
| 3 | Acta Materialia | 300 | United Kingdom | 7.656 |
| 4 | Intermetallics | 277 | United Kingdom | 3.398 |
| 5 | Scripta Materialia | 241 | United kingdom | 5.097 |
| 6 | Materials Design | 129 | Netherlands | 6.289 |
| 7 | Materials Letters | 129 | Netherlands | 3.204 |
| 8 | Journal of Applied Physics | 109 | United States | 2.286 |
| 9 | Entropy | 106 | Switzerland | 2.494 |
| 10 | Journal of Magnetism And Magnetic Materials | 105 | Netherlands | 2.717 |
| 11 | Scientific Reports | 102 | United Kingdom | 3.998 |
| 12 | Surface Coating Technology | 102 | Netherlands | 3.784 |
| 13 | Metals | 101 | Switzerland | 2.420 |
| 14 | Metallurgical and Materials Transactions A Physical Metallurgy and Materials Science | 97 | United States | 2.050 |
| 15 | JOM | 96 | United States | 2.054 |

*3.3 Author's profiling*

Based on the authors' publication rate in HEAs, the top 15 most active researchers are listed in Table 3. This table also includes research numbers in HEAs, all publications number of these researchers, total citations, and citation per article. It is noticeable from the table that these 15 authors account for 22.4% of all analyzed publications (6796) in the time frame of this study. That means there are so many researchers working on HEAs. Yong Zhang is the most fruitful author with 215 publications in HEAs (86.7% of all publications he has done). Following him, Liaw, peter K., and Jien-Wei Yeh have got 201 and 165 published studies in HEAs. Furthermore, Liaw PK ranked second because he has more publications than Yeh JW, but Yeh focused more on HEAs, with 74.3 percent of all of his studies (165 out of 222 publications).

It is commonly known that the number of publications measures the author's academic production. Although, the number of citations evaluates the influence of published studies [21]. Furthermore, most citation databases recently use the h-index as a bibliometric clue to assess the value of a scientist's cumulative research contributions and their widespread influence [22]. The h-index represents the number of publications with references equal to or higher than this "h" number. A great point is most of these authors have an h-index of more than 50. Besides this, Liaw got a greater h-index as compare to Zhang and Yeh, but Liu CT has the greatest h-index in the listed authors; it returns to he has a significant publication rate generally. So, Liaw and Yeh have a significant role in the HEA community because they got a high number of citations which is 24737 and 22210, Zhang also has a great impact in the field with the greatest number of publications in the area.

**Table 3.** Fifteen top innovative researchers along the study period

| No | Author | Publication in the field of HEAs | All publications | H-index | Total citations | Citations per item |
|---|---|---|---|---|---|---|
| 1 | ZHANG Y | 215 | 248 | 55 | 13618 | 54.91 |
| 2 | LIAW PK | 201 | 761 | 67 | 24737 | 32.51 |
| 3 | YEH JW | 165 | 222 | 65 | 22210 | 100.05 |
| 4 | LIU Y | 145 | 1596 | 58 | 21435 | 13.43 |
| 5 | KIM HS | 84 | 576 | 52 | 12184 | 21.15 |
| 6 | WANG L | 81 | 144 | 23 | 1725 | 11.98 |
| 7 | ZHANG H | 80 | 103 | 24 | 1872 | 18.17 |
| 8 | LIU CT | 75 | 828 | 99 | 46100 | 55.68 |
| 9 | MISHRA RS | 71 | 428 | 56 | 18269 | 42.69 |
| 10 | WANG H | 70 | 142 | 38 | 4675 | 32.92 |
| 11 | LU ZP | 69 | 239 | 56 | 16095 | 67.34 |
| 12 | QIAO JW | 69 | 219 | 35 | 4345 | 19.84 |
| 13 | MURTY BS | 68 | 82 | 14 | 1202 | 14.66 |
| 14 | LIU B | 67 | 78 | 19 | 1383 | 17.73 |
| 15 | GAO MC | 64 | 82 | 32 | 5651 | 68.9 |

*3.4 Countries/regions with most HEA publications*

As far as can be noticed from

, 15 top countries have been ranked based on the rate of publications in the HEAs field. Besides, **Hata! Başvuru kaynağı bulunamadı.** shows the rate of studies published in regions. The list of most 15 active countries contains 5 Asian countries, 7 European countries, the USA and Australia are also included. A significant rate from China could be seen from the table, total research published in HEA located in China (2935). The USA is following it by 1518 studies published in that field. At the same time, a European country (Germany) is listed in third place with 542 publications. The authors from China have a tremendous role, with a rate of ~36.15% out of all publications. The USA has a ratio of ~18.7% researches. Germany and India are almost near to 6.5% for each of them, they have got ~6.67% and ~6.33% respectively. Furthermore, a huge number of publications can be found in the East Asia region, including China, Taiwan, Japan, and South Korea. The most significant region (East Asia) could get 49.77 percentage out of total publications in that period. North America (the USA) has gained 18.7% of published studies. Europe (Germany, France, England, Sweden, Spain) is also one of the most noticeable regions that reached 16.59%.

**Table 4.** Fifteen most fruitful countries in HEAs studies during the period of research

| No | Country | Region | Number of publications | Percentage of total published studies |
|---|---|---|---|---|
| 1 | China | East Asia | 2935 | 36.15 |
| 2 | USA | North America | 1518 | 18.7 |
| 3 | Germany | Europe | 542 | 6.67 |
| 4 | India | South and east Asia | 514 | 6.33 |
| 5 | Taiwan | East Asia | 371 | 4.57 |
| 6 | Japan | East Asia | 367 | 4.52 |
| 7 | South Korea | East Asia | 320 | 3.9 |
| 8 | Russia | East Europe and North Asia | 264 | 3.25 |
| 9 | France | Europe | 240 | 2.95 |
| 10 | England | Europe | 236 | 2.92 |
| 11 | Ukraine | East Europe | 194 | 2.42 |
| 12 | Sweden | Europe | 191 | 2.35 |
| 13 | Australia | Australia | 173 | 2.13 |
| 14 | Poland | East Europe | 137 | 1.7 |
| 15 | Spain | Europe | 117 | 1.44 |

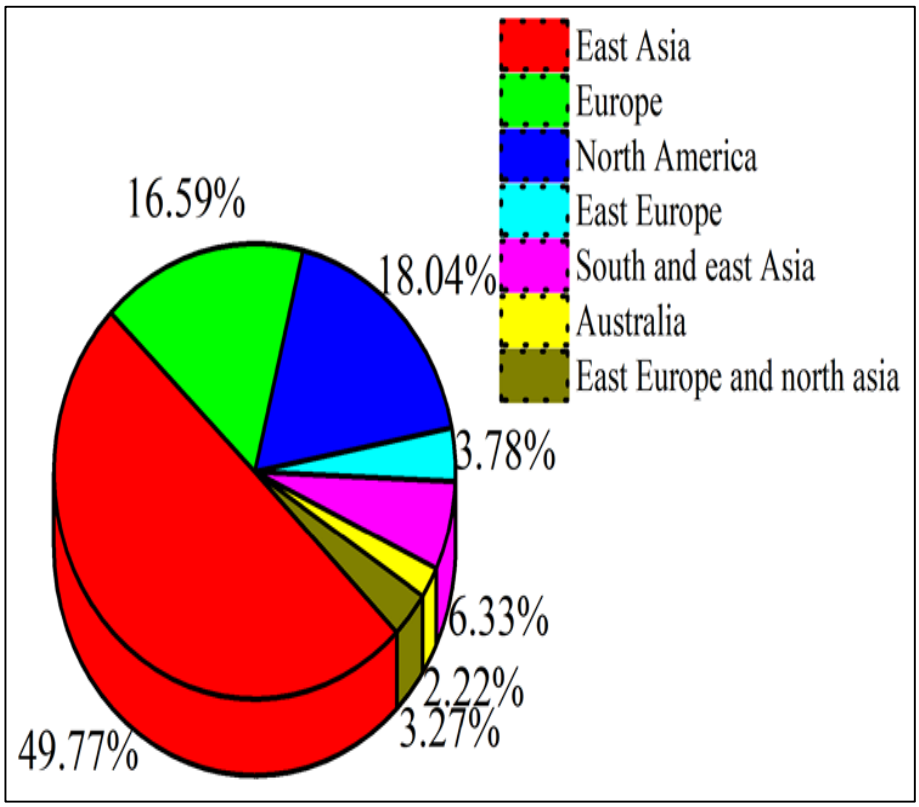


**Fig.2.** Contribution of regions in top 15 active countries in the field of HEAs from 2004 through 2020

## 4. Conclusion

Researchers and policymakers need to take a quick look at HEA research and anticipate the dynamics of research by the quickness and the scale of development. This bibliometric analysis covers the gap in research under these conditions by analyzing the HEA study published globally in different fields of study and institutes from 2004 to 2020. In conventional alloys, there was a relatively limited study with alloys because of base element phenomena. In contrast, researchers' new novel alloys get more attention, studied in HEAs gradually increased in the early twenty-first century. Between 2012 and 2014, there was a significant rise in HEA research. In the last three years, studying with HEAs increased, and the most important published number was in 2020 (1833). The linguistic analytics showed that the major language of HEA publications in English (97.75%). An article titled "*Nanostructured high-entropy alloys with multiple principal elements: Novel alloy design concepts and outcomes"* which was published in 2004 got the greatest citation number (4123), and two review articles listed in the second and third-row which are "*Microstructures and properties of high-entropy alloys"* in 2014 and *"A critical review of high entropy alloys and related concepts"* in 2017; they gained 2397 and 2009 citations respectively. "*Journal of Alloys and Compounds"* has the largest number of publications in the HEAs field with 677 studies. Zhang Y has the most published articles (215) in the field of HEAs with 13618 citations. Yeh JW is also one of the top three authors in the HEA field with 165 published researches, 22210 citations and it makes 100.05 citations per study. Authors from China have 2935 published studies and also 1528 researches from the USA published in the period of this study. The most involved regions are East Asia (49.77%) and Europe (16.59%) according to the highest number of published articles in HEAs. This present review has more identifications like most cited HEA studies, most active journals in that field, top innovative authors, and contributing to international institutes in HEAs. This study will give benefit early researchers by guiding them and helping them. Besides this, it also helps identify the possible institutes/authors to exploit the synergistic collaborative partnership.

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