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Review scientific paper

Investigating relationships between intrinsic properties, preparation parameters of coal and coke quality: A Systematic Literature Review

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Abstract
The purpose of this study is to review some of the key research concepts related to metallurgical coke. As the research landscape for coke metallurgy is evolving, researchers are increasingly interested in the effects of the intrinsic properties of coal, coal preparation parameters, and the technological conditions of coke production on the quality of metallurgical coke. As part of this review, a specific protocol, content analysis and thematic coding of cases of the "Preferred Reporting Items for Systematic Review and Meta-Analyses" method were used to investigate the simultaneous effect of these two parameters on the quality of coke in selected journal articles. A review of 118 articles was conducted, including their abstract, introduction, methodology, and results. According to the results of this study, coal blends and coal particle sizes have a direct effect on the three sections of coke mechanical properties, coke texture, and coke reactive properties. Reviewing various articles has shown that the presence of fatty coals in smaller size distribution, combined with larger-sized weak coals, leads to the formation of a stronger structure in the produced coke. However, this does not guarantee an improvement in the coke reactivity parameters. On the other hand, increasing the blending ratio of coking coals in the final mixture for producing normal-sized coke (dimensions smaller than 3 millimetres) improves the coke reactivity parameters. Studies investigating coke structure have demonstrated that a cohesive mosaic structure in high-quality cokes results from well-distributed maceral blends of coking coals with optimal size distribution among other coals.

Keywords:
coal preparation; coke quality; coke making; systematic literature review

1. Introduction

Energy plays a vital role in driving global economic growth. Over the past five decades, the demand for energy resources has witnessed a rapid surge as societies around the world continue to develop (**Schandl et al., 2016**). However, in recent years factors such as technological advancements and increased awareness of the need to reduce greenhouse gas emissions and industrial make-smart have led to the growth of the share of renewable energy production and utilization in the global energy mix (**Rani et al., 2020**). In spite of that, it is important to note that numerous industries remain heavily dependent on conventional energy sources including coal, oil, and gas. This reliance on traditional energy sources persists in the present day. In fact, it is noteworthy that in 2013, traditional energy sources accounted for a substantial 65% of the overall energy production (**Zafar et al., 2019**). Furthermore, studies note that coal still makes up 29% of the global primary energy (**Medunić et al., 2018**). Coal remains one of the most significant sources of energy in many countries, particularly industrialized countries, despite extensive changes in the energy consumption structure and the development of energy production methods (**Zhang et al., 2023**). China, the United States, India, Russia, and Japan are the five major consumers of coal, accounting for 76% of the global coal consumption (**Fiket et al., 2022**). At the same time, coal is a non-renewable natural energy source and the world's most abundant fossil fuel in a wide range of industries (**Putilova, 2023**). In their study, **Medunić et al., (2016)** showed that coal accounted for approximately 40% of the global electricity generation. Coal transforms into three phases: liquid, solid and gas. There are three main sectors of consumption: combustion, conversion, and carbonization (**Mandal & Maity, 2023; Rantitsch et al., 2020; Granda et al., 2014**). One of the products of carbonization is metallurgical coke. The production of coke is one of the main industrial uses of coal. There is a heterogeneity in the physical and chemical properties of coke, which is a cellular and porous material. Depending on the production method, coke can be divided into three categories: semi-coke,

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metallurgical coke and casting coke (**MacPhee et al., 2013; Chen et al., 2022; Zhang et al., 2022**). While many advancements have been made in steelmaking, blast furnaces remain the dominant method of producing steel worldwide. Conversely, metallurgical coke plays a critical role in the manufacturing of steel and iron (**Smith, 2015; Lomas et al., 2021; Zhou et al., 2023**). Coke plays an important role in blast furnaces as a heat source, a reducing agent, a dust filter, and a permeability agent. There is a direct correlation between the quality of metallurgical coke used in blast furnaces and the stability of the conditions in the furnace (**Pang at al., 2023; Wei et al., 2022; Roest et al., 2016; Lee et al., 2019**).

First and foremost, it is necessary to determine and recognize the main components of metallurgical coke in order to produce suitable coke for metallurgy. As a whole, metallurgical coke has four main characteristics and properties that indicate its quality, namely physical properties, chemical properties, thermal properties, and mechanical properties (**Hou et al., 2022; Wu et al., 2022; Gulyaev et al., 2013; Zhang, 2019**). A hypothesis suggests that the characteristics of CRI and CSR in coal are interconnected and can be linked to specific geological parameters. This connection is attributed to coal being a carbon-rich biomass that has undergone geological processes in conjunction with various mineral and organic carbon deposits (**Dyczko, 2023**).

As a result of selecting suitable coal and creating adequate technical conditions, it is possible to achieve desirable coke quality properties. Due to the difficulty of changing industrial conditions (**Hu et al., 2021; Yu & Shen, 2018; Zagainov et al., 2011**), the intrinsic parameters and coal preparation are the most important and influential parameters on the quality of coke produced after considering the production factors or technical conditions of coking, which are usually considered constant. Due to this, selecting the right coal is essential to ensure high-quality coke (**Chelgani et al., 2016; Xing et al., 2019; Kumar et al., 2008**). There are relatively few research papers that have concurrently explored both the composition of coal blends and the distribution of coal particle sizes as essential parameters in the process of coke making. Within the literature, one can find studies focusing either on the composition of coal blends or on the distribution of coal particles. It can be argued that there is no article that systematically investigates the impact of variations in these two factors on the qualitative characteristics of coke, including its strength and reactivity indices. For a more comprehensive understanding, it is recommended to refer to scholarly articles that have focused on the analysis of these specific parameters (**Yang et al., 2018; Vasko et al., 2005; Sharma et al., 2007; Gupta et al., 2007; Rejdak & Wasielewski, 2015**). In order to address this shortcoming, the present article reviewed a systematic review of articles published around the world. It focused on investigating the relationship between these two coal preparation parameters and coke quality.

2. Methodology

There is no doubt that a literature review is an essential component of any research project (**Kitchenham, 2004**). The purpose of the literature review is to evaluate and analyze the literature in order to identify potential gaps. A research gap should be identified in a way that, if it is addressed, it serves as a basis for strengthening the study and research field (**Fisch & Block, 2018**). To avoid biasing the results, this study has been conducted as a systematic literature review for the purpose of enhancing accuracy by considering a quantitative research approach (**Page et al., 2021**).

2.1. Systematic literature review

In systematic literature reviews, existing studies are combined, the current state of knowledge in a given field is assessed, and research gaps are identified. To identify documents for inclusion in the review, this method uses a rigorous search strategy utilizing keywords (**Mallett et al., 2012**). Systematic approaches reduce biases in literature selection and provide reliable results for researchers in a particular field, since they are systematic in nature. As a result, this article features a systematic review based on the PRISMA standard that follows a specific procedure, as shown in **Figure 1** (**Snyder, 2019**).

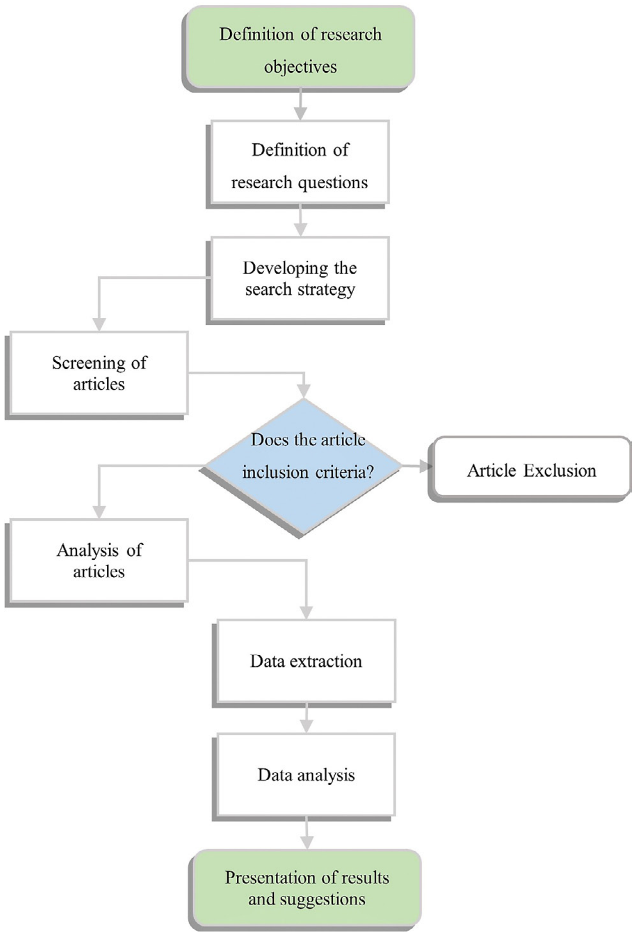


Figure 1: Systematic review process

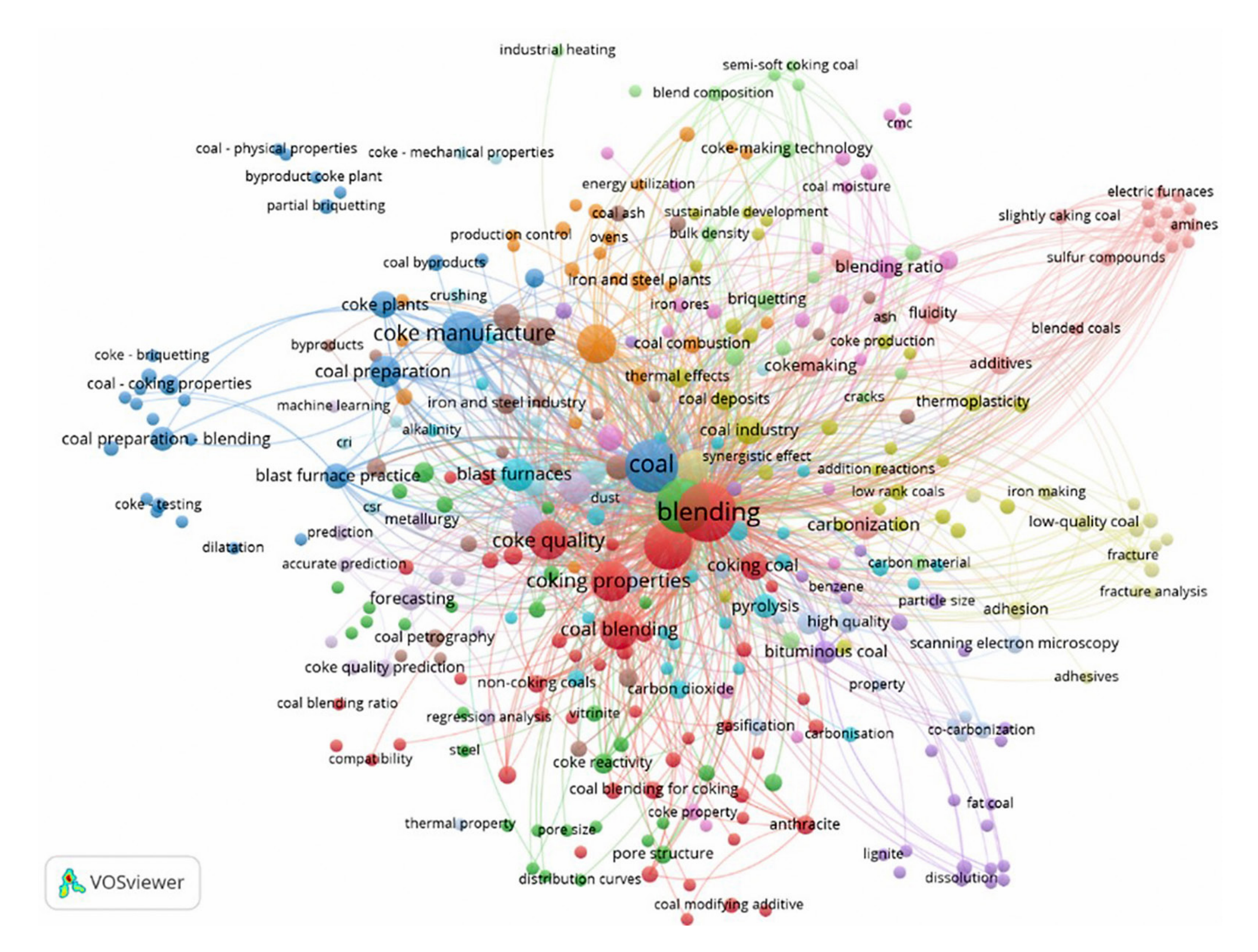


Figure 2: VOSviewer output for keyword network comparison (**Van Eck & Waltman, 2017**)

In a systematic review, the work is typically organized according to the defined objective. There is usually an attempt to establish criteria for screening, inclusion rules for the review, the method of data extraction from the article, and ultimately, the data analysis to follow a specific process. Therefore, in this article, several primary criteria for initial screening have been applied based on other similar systematic reviews, which include: 1. Proximity to the research objective, 2. Coverage of the search keywords, and 3. Research-oriented nature of the article under review. The main rules for including an article in this work are: 1. the article being available online, 2. the article being in English, 3. the title, abstract, and conclusion of the article being close to the current work, and 4. the article not being a review article. The method of data extraction from the article and the analysis of the articles have been carried out based on a collaborative team task of three individuals, as described in the following sections.

2.2. Research objectives

In order to attain a comprehensive understanding, determine the extent to which coal preparation parameters influence coke quality, critique previous works, as well as clarify the role of these two parameters in the coke making process, the following objectives were established.

- Identifying the coking process' effective parameters and monitoring them.
- Identifying and classifying the methods used to evaluate the coking process's effective parameters.
- Determine existing priorities for coking research in the future.

2.3. Defining the research questions

To accomplish the above objectives, the following four research questions were investigated with regard to coking in order to conduct a systematic review:

- What were the general characteristics of the coke used in the selected articles in terms of quality?
- During the time period under review, what modifications have been made to the parameters of coal preparation in relation to coking?
- Which parameters of coke quality have been examined in the research regarding the effect of coal size

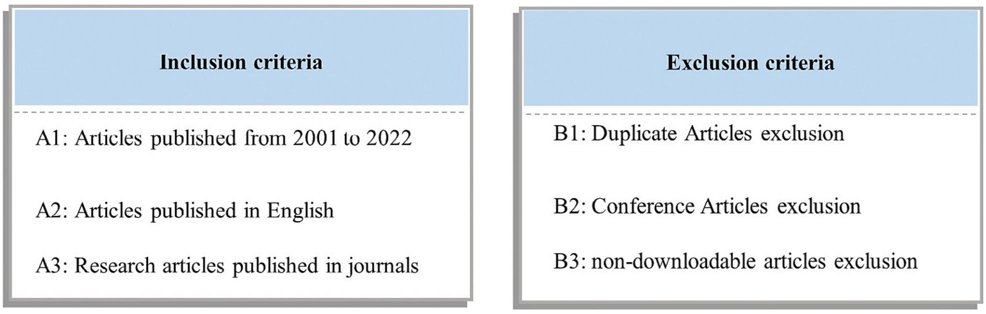


Figure 3: Input and output criteria

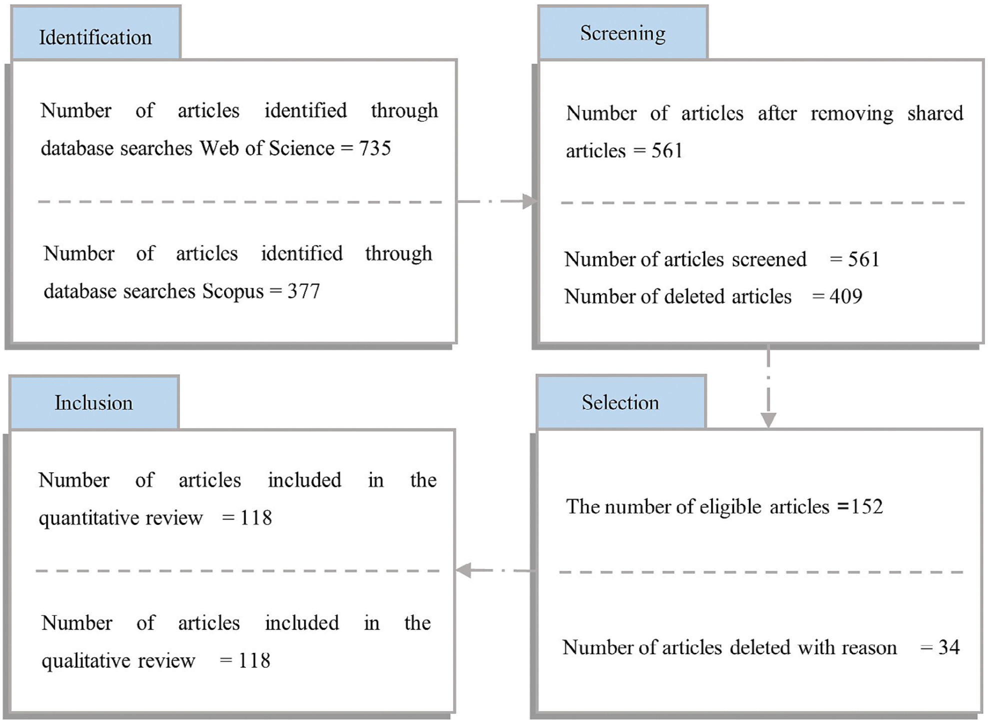


Figure 4: Article screening procedure

distribution and mixture as coal preparation parameters?

- How can research on coke quality parameters be directed in the future?

Answers to these questions are important for achieving research objectives, namely, determining the importance, role, and placement of coal preparation parameters in terms of coke quality in scientific research. Furthermore, to understand the effects of the mentioned parameters on the quality of coke produced worldwide over the past 20 years.

2.4. Search strategy

As part of the systematic review process, a predetermined schedule should be followed with a comprehensive schedule-implementation plan to ensure the review process is conducted in a systematic manner (**Mallett et al., 2012**). A systematic approach emphasizes the need to carry out a comprehensive search of relevant literature using a specified database to develop a high-quality report, which is grounded in a thorough, objective, rigorous, and traceable review process (**Van Dinter, 2021**). An analysis of Web of Science (WOS) and Scopus databases was conducted for the purposes of data collection and analysis in this article. The two databases are currently among the best-known and most reliable bibliographic databases in the world, often used by researchers from a wide range of fields (**Pranckutė, 2021; Mongeon & Paul-Hus., 2016; Martín-Martín et al., 2018; Rovira at al., 2019; Archambault et al., 2009**). The use of Visualization of Similarities (VOS) viewer software prior to conducting the search process in these two databases was carried out to identify the combination of prominent and frequent words within the field of coking shown in **Figure 2**.

Due to its network-based design, VOSviewer is more efficient than multidimensional scaling for creating bibli-

Table 1: Keyword search results

The investigated parameters	No	Key words	The number of articles selected from Scopus	The number of articles selected from WOS	Total *Articles*
Coal Blend & (1 to 5)	1	Coke mean size	6	19	25
	2	Coke reactivity index	66	14	80
	3	Coke strength after reaction	27	124	151
	4	Coke quality	114	325	439
	5	Coke Texture	17	64	81
Coal Size Distribution & (1 to 5)	1	Coke mean size	35	54	89
	2	Coke reactivity index	9	13	22
	3	Coke strength after reaction	13	12	25
	4	Coke quality	72	95	167
	5	Coke Texture	18	15	33
Total Articles			377	735	1112

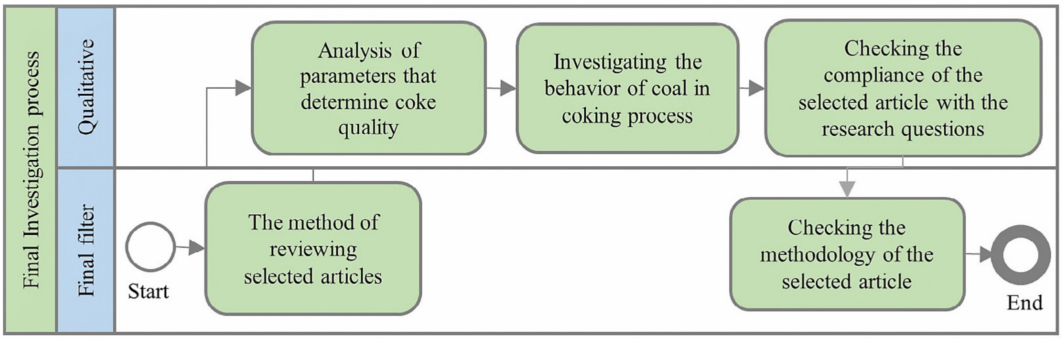


Figure 5: The final article filter

ometric maps (**Van Eck & Waltman, 2017; Tamala et al., 2022**). According to the mapping of the VOSviewer software, the extracted keywords were divided into two categories of frequently used keywords. The first group in the field of coking: coke strength after reaction, coke mean size, coke reactivity index, coke texture and coke quality the second group in the field of coal preparation parameters: coal particle size distribution, coal blends, and inherent coal properties. According to **Figure 3**, articles were selected according to input and output criteria. This systematic review implemented the search strategy in accordance with the four steps, as shown in **Figure 4**.

2.5. Article selection

Based on the selected keywords, the search produced 1112 articles, as shown in **Table 1**, which subsequently reduced to 561 articles after removing the common articles. During this search process, it was ensured that each aspect of coking was considered. Considering the difficulty of accessing sources and conferences, as well as the fact that repeating review articles is not very common in systematic literature reviews, it was decided not to review printed books, conferences, or review articles in order to ensure that the research originated from academic sources (**elimination of 409 articles**).

A number of duplicate articles, articles appearing more than once in the combination of keyword pairs, and articles containing incomplete bibliographic information were removed from the results in order to refine them further. The study also excluded articles in which coking was mentioned as a short reference point or research topic. According to **Figure 5**, the final filtering steps were followed for the articles.

According to **Figure 5**, 152 articles related to the existing study were selected after a final screening determined in **Figure 5** and analyzing the titles and abstracts of the articles. A total of 118 articles were selected for downloading after carefully reviewing the title, abstract, working method, and conclusion of all 152 selected articles. The 34 articles that were removed included 12 duplicates, 6 that were not downloadable, and 16 that were not relevant to the topic. The final articles were chosen based on their conformity to the three research objectives, the research questions, and the input and output criteria in **Figure 3**. In addition, they were selected based on the final filter, as shown in **Figure 5**.

2.6. Data extraction

Data extracted from 118 final articles were categorized into two categories: primary data and data derived

Table 2: A sample review of the final articles (**Kimura et al., 2019; Nomura& Arima, 2013**)

Reference	key words	Methodology of the article	Coking process	Coal parameters	Coke parameters	Publishers	Research question	research goal	citations
Kimura et al., 2019	Coke; coke breeze; fissure; Gaudin-Meloy-Harris size distribution function; voidage	Image Processing	During, After	Coal Blending	Coke Quality, Coke Cracks	ISIJ International	2&4	1	1
Nomura& Arima, 2013	Mean coke size; Contraction; Coal blend	Laboratory Scale Investigation	During, After	Coal Rank	Coke Mean Size, Coke Contraction Ratio	Fuel	1to 4	1&3	26

from the article's text. Primary data for the article included the title, author, publication date, citation, and keywords. In addition, the text of the article yielded the following data: the analysis method, the parameters examined in the article, and the proximity of the article to the research questions. During the data extraction process, the articles were reviewed based on the type of investigation and the degree to which their methodology conformed to the research questions, as well as their degree of conformity with the research questions; two of the initial results of this review can be found in **Table 2**.

3. Data analysis using statistical methods

The reviewed articles were analyzed based on publication year, coking process timeframe, coking parameters, coal parameters, article analytical method, article publications, and first author's country of origin.

3.1. Article publication data

Articles published between 2001 and 2019 were reviewed. **Figure 6** illustrates the number of articles that have been published based on frequency and time of publication. In 2019, the growth rate of publishing articles increased significantly in relation to the previous year, based on an examination of 118 selected articles. That year, there were significant increases in the number of selected published articles (as evidenced by the 1112 initial articles in **Table 1**). Additionally, for 118 selected articles from 6 articles in 2018, articles (**Yang et al., 2018; Stepnov et al., 2018; Nomura, 2018; Singh et al., 2018; Liu et al., 2018; Zelenskii et al., 2018**), to 15 articles in 2019, articles (**Zhang, 2019; Kimuraet al., 2019, Nomura, 2019; shaik et al., 2019; Zhang et al., 2019; Sun et al., 2019; Otsuka et al., 2019; North et al., 2019; Probierz & Marcisz, 2019; Fang et al., 2019; Xing et al., 2019; Florentino-Madiedo et al., 2019; Lech et al., 2019; Vasudharini et al., 2019; Yang et al., 2019**), which are shown in **Figure 6**.

This is a significant increase. This growth indicates a significant upward trend in content production in the field of coal and coke over a one-year period. Increasing

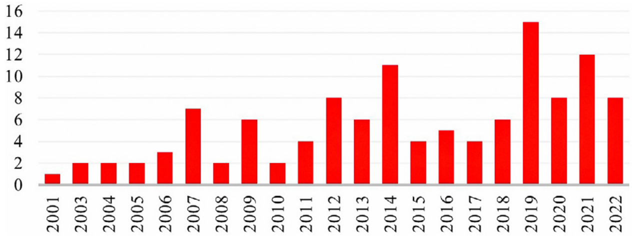


Figure 6: Annual article publication statistics

the number of articles from 6 articles in 2018 to 15 articles in 2019 indicates a more than doubled effort in content production. This growth may reflect researchers' increased focus on the challenges in this field or a broader strategy. Analysing the parameters examined in these articles is essential to understanding the impact of this increase. Such a growth trend could lead to more audience engagement, better visibility, and expansion of the topics under investigation in the field of coal and coke.

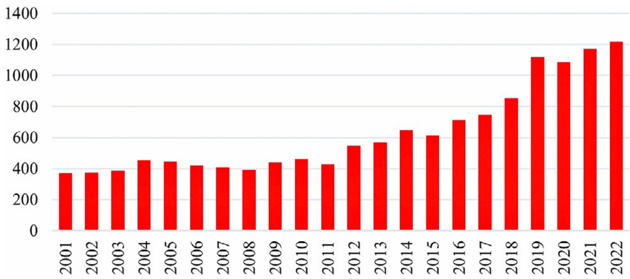


Figure 7: Total number of published articles in 2019 with the search of two keywords "coal" and "coke" in the databases WOS and Scopus

The examination also showed that this trend is consistent in both datasets (Scopus and WOS) for a better understanding. The words "coal" and "coke" were searched in these two databases, and the results of this search are presented in **Figure 7**. Furthermore, according to the statistics of the World Steel Association in **Figure 8**, global crude steel production increased by 3.4% in 2019 compared to 2018 (**Iron & Works, 2020**). This growth in steel production statistics could itself be one of the factors contributing to the increase in articles in

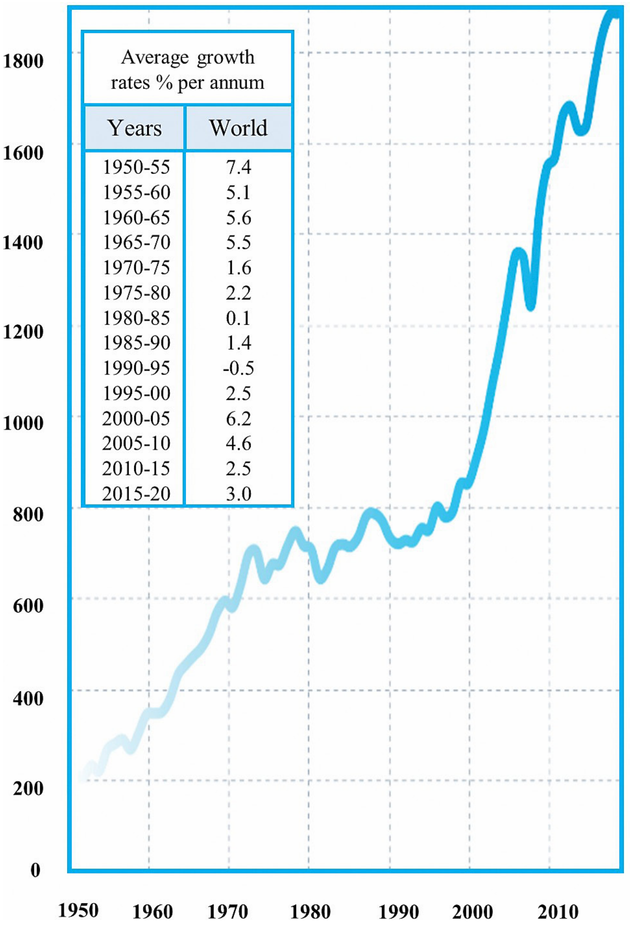


Figure 8: Statistics for 2018 and 2019 by the Steel Association (**worldsteel.org**)

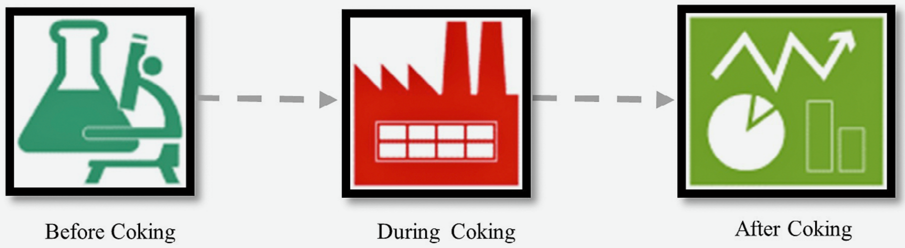
that year since some of the published articles receive support from one or more national sponsors.

The iron and steel industry consumes over 20% of the total industrial energy consumption worldwide (**worldsteel.org**). Due to its importance in the steel industry, large-scale blast furnaces provide 70% of hot metal (**pig iron**) for steel production worldwide (**Azadi et al., 2023**). As a result, researchers have emphasized its importance in their research. Furthermore, increasing production or organizational incentives may result in scientific advancement and growth in a particular field at different times (**Radzvilas et al., 2023**). The growth of steel production may be one of the reasons for the increase of articles in the field of metallurgical coke this year, considering that some articles have utilized financial support from a variety of companies for their research; for example, articles (**Otsuka et al., 2019; Rejdak et al., 2022; Kuyumcu & Sander, 2014; Vega et al., 2021; Abel et al., 2009**).

3.2. Coking process timeframe

Based on data analysis, 118 selected articles revealed that researchers in their studies mostly focused on examining the quality/properties parameters of coal blends and their impact on the characteristics of produced cokes in the coking process. On the other hand, another segment of research focused on the quality/properties of the produced cokes regardless of the type of coal consumed. Overall, 62% of the reviewed articles in this study have explored coal parameters examined before coking, mostly encompassing the intrinsic properties of coals, analyzing coal properties (including macerals, coal structure and area, sulfur, ash), investigating coal blending effects on coke quality, and investigating coal size distribution effects on coke properties; In **Figure 9**, (**Yang et al., 2018; Sharma et al., 2007; Gupta et al., 2007; Rejdak & Wasielewski, 2015; Nomura, 2018; Zelenskii et al., 2018; Sun et al., 2019; Probierz & Marcisz, 2019; Yang et al., 2019; Mianowski et al., 2021; Gutiérrez Berna et al., 2011; Jha et al., 2021; Nyathi et al., 2013; Silva et al., 2016; Parsad et al., 2001; Zhang et al., 2004; Shen, 2012; shen et al., 2020; Díaz et al., 2008; Pankaj et al., 2021; Tiwari et al., 2014; Jeuken et al.,2021; Shui et al., 2014; Kumar et al., 2008; Li et al., 2022; Dash et al., 2007;Burat et al., 2015; Miroshnichenko & Meshchanin, 2021; Ghosh et al., 2022; Díaz-Faes et al., 2007; Smędowski et al., 2011; Krzesińska et al., 2009; Rejdak et al., 2021; Arendt et al., 2006; Li et al.,2021; Montiano et al.,2016; Jha et al., 2020; Krzesińska et al., 2010; Prachethan Kuma et al., 2007; Gupta et al., 2022; Fernández et al.,2012; Shui et al., 2011; Alvarez et al., 2003; Rejdak et al., 2022; Stankevich & Stankevich et al., 2012; Kuyumcu & Sander, 2014**); the parameters that have been investigated in selected articles after the coking process, meaning in the laboratory stage based on the properties of the produced cokes, with the title of quality/properties of coke include: properties of produced coke, coke structure, coke strength, coke reactivity indices, and coke mean size (**Kimura et al., 2019; Nomura & Arima, 2013; Zhang et al., 2019; Otsuka et al., 2019; North et al., 2019; Kurniawan et al., 2022; Nagashanmugam et al., 2015; Suresh et al., 2012; Wei et al., 2022; Miyashita et al., 2021; Lyalyuk et al., 2012; Geng et al., 2020; Saito et al., 2014; Kanai et al., 2012; Nomura et al., 2004; Chen et al., 2020; Guo et al., 2020; Gornostayev et al., 2006; Agra et al., 2021; Jenkins et al., 2010; Casal et al., 2007; Colorado-Arango et al., 2021; Koszorek et al., 2009; Klika et al., 2020; Krzesińska, 2013**): production coke properties, coke reaction indices, and average coke size.

This article does not investigate coking (**coal to coke**) alone. Based on a review of the articles, it was concluded that the coking process has received little attention due to the complexity of the process and the difficulty in reaching the plastic zone during coal conversion into coke due to the high temperatures and technical conditions of the conversion process (**Guelton, 2017; Kokonya et al., 2013**). Therefore, determining coal conversion boundary conditions is a complex process that requires effort and influence (**Saito et al., 2014; Hayashi et al.,**



- 62 percent of the articles have investigated the parameters of coal and coke quality
- 23 percent of the articles have focused solely on examining the parameters of coal quality
- 8 percent of the articles have focused solely on examining the parameters of coke quality
- 5 percent of the articles have addressed the inherent parameters of coal, technical production conditions, and the quality of the produced coke
- 2 percent of the articles have addressed the technical production conditions, and the quality of the produced coke

Figure 9: Analysis of the coking period

2014). Additionally, the establishment and stabilization of laboratory conditions required for the investigation of the coal to coke conversion process require the establishment and maintenance of exact laboratory conditions for repeated measurements, which are both costly and time-consuming (**Probierz & Marcisz, 2019**). Attempting to reveal the mysteries of coking is met with numerous additional obstacles. The complex interaction among different coal preparation factors introduces a level of intricacy to the complete procedure. Comprehending these factors necessitates a comprehensive and methodical strategy that takes into account the hierarchical impact they have on the qualitative characteristics of coke.

3.3. Coal parameters

Among the coal parameters reviewed, a coal blend was examined in 43% of the publications **Figure 10**. A case such as this one demonstrates the importance of carefully examining the coal mixture utilized in the coking process. Coke production properties, such as reactivity, resistance, average size, and coking pressure, were affected by the coal mixture used during the coking process (**Rejdak et al., 2021**). In contrast, the right mixture is crucial to creating a coke with a better reaction rate (**Yuan et al., 2020; Dash et al., 2012; Sharma et al., 2014**). In recent years, advancements in analytical techniques have enabled researchers to delve deeper into the complexities of coal blending and its impact on coke properties. Researchers have been able to elucidate the structural and chemical changes occurring during the coking process, which occur as a result of changes in the coal blend mixture.

3.4. Coking parameters

A review of articles on the coking process revealed that 27% of them investigated coke quality, as shown in

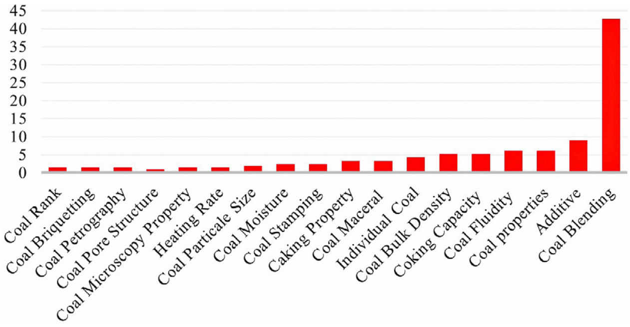


Figure 10: Coal parameters discussed in the articles

Figure 11. Additionally, CSR, CRI, coking pressure and coke texture have been identified as significant coking parameters in articles. According to this case, these items are essential to the quality of coke produced in the coking process.

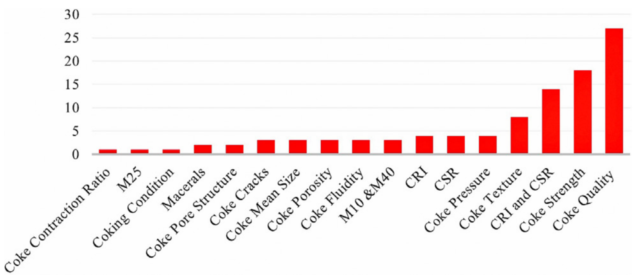


Figure 11: The parameters of coke examined in the articles

3.5. Journal publication

Upon review of the publications, it was found that the following 5 journals had published the most articles: Iron making & Steelmaking, Fuel, Coke and Chemistry, ISIJ International, and Fuel Processing Technology, as shown in **Table 3** and **Figure 12**.

Table 3: The parameters of coke examined in the articles

No	Publication title	No	Publication title	No	Publication title
1	Fuel	11	Journal of Analytical and Applied Pyrolysis	21	Journal of Central South University
2	Ironmaking & Steelmaking	12	Energies	22	Gospodarka surowcami mineralnymi
3	Coke and Chemistry	13	Energies	23	Sustainability
4	Fuel Processing Technology	14	Coal Preparation	24	Metals
5	ISIJ International	15	Journal of the Operational Research Society	25	Biomass and Bioenergy
6	International Journal of Coal Geology	16	Transactions of the Indian Institute of Metals	26	REM-International Engineering Journal
7	International Journal of Coal Preparation and Utilization	17	Metallurgical Research & Technology & Modeling	27	Physicochemical Problems of Mineral Processing
8	Metallurgical Research & Technology	18	Energy Sources	28	Information Sciences
9	ACS omega	19	Journal of Thermal Science and Technology	29	Steel Research International
10	Energy & fuels	20	Ingeniería e Investigación		

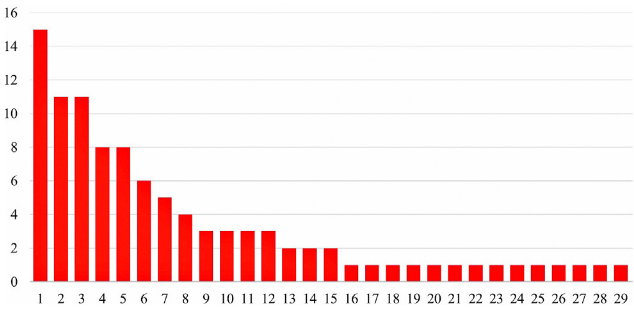


Figure 12: The parameters of coke examined in the articles

Upon reviewing the articles, it became clear that the authors preferred to publish their articles in Fuel magazine (29%), which is likely a result of the magazine's specialization as well as its high scientific ranking. In other words, the goal of reviewed articles was to investigate and resolve environmental issues and pollution related to the coke making process and to resolve defects in the field of coke quality (**worldsteel.org; Azadi et al., 2023; Radzvilas et al., 2023; Rejdak et al., 2022**). Thus, the authors paid particular attention to magazines with a high ranking in the world rankings focused on energy and fuel.

3.6. Article analysis method

An analysis of the methodological approaches used to analyse the selected articles revealed five major approaches: modelling, laboratory-scale review, pilot-scale review, simulation, and theoretical review (see **Table 4**).

Since laboratory investigations can be controlled better than pilot conditions, have higher precision, and can be completed in a shorter amount of time and at a lower cost (compared to the pilot conditions), they have been of great importance in reviewing scientific articles. As a result of reviewing the articles, it was discovered that modelling is divided into two parts: the mathematical

Table 4: Review articles analysis method

No	Article analysis method	Number of cases	%	No	Article analysis method	Number of cases	%
1	Laboratory scale Investigation	54	46	8	Pilot Scale Investigation & Modelling	1	1
2	Modelling	27	23	9	Laboratory Scale Investigation & Image Processing & Modelling	1	1
3	Pilot Scale Investigation	12	10	10	Data Processing & Modelling	1	1
4	Investigation	7	6	11	Image Processing	1	1
5	Simulation	3	3	12	Numerical Model	1	1
6	Laboratory & Pilot Scale Investigation & Image Processing	3	3	13	Numerical Model & Image Processing	1	1
7	Laboratory & Pilot Scale Investigation	2	2	14	Pilot Scale Investigation & Image Processing	1	1

modelling to formulate the relationships between the parameters investigated in the coking process, and the mathematical modelling to explain the dynamics of the process. Nevertheless, a pilot study designed to verify the results obtained at the laboratory stages and compare them to those obtained at the pilot scale has been examined in the following articles (**Matsuo et al., 2014; Yadav et al., 2004; Ghosh et al., 2020; Piechaczek et al., 2015; Lech et al., 2019; Xiang et al., 2021; Casal et al., 2003; Pusz et al., 2009**). Many of the articles dealing with the parameters have been reviewed theoretically in order to confirm previous studies (**Pusz and Buszko, 2012**). There have been several articles that have used simulation to determine the performance of the coking process and identify errors and deficiencies (**Alvarez et al., 2007**).

3.7. Publisher's country

Based on a review of 118 selected articles, the 10 countries with the most number of articles published were: India, China, Poland, Japan, Spain, Ukraine, Australia, Germany, Brazil and the United States, as shown in **Figure 13**. An analysis of the list of the major producers of coal and coke also reveals the same countries to some extent (**Brooks et al., 2023**). Consequently, it can be concluded that the selection of selected articles has been accomplished correctly.

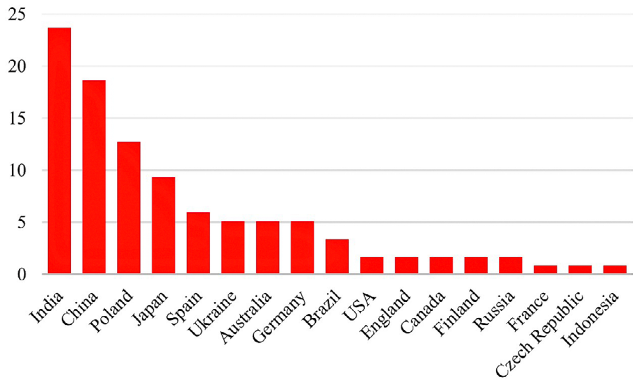


Figure 13: Country of the article's responsible author

4. Responding to questions

4.1. The quality parameters of coke in the selected articles

As a result of reviewing 118 selected articles, it has been determined that coke quality parameters cover a wide range of variables, which can be divided into three general categories (see **Figure 14**). The content of the articles indicated that there is a correlation between the three groups of coke indicators, as shown in **Table 5**. The coke texture influences the majority of the coke parameters listed in **Table 5**. This is due to a number of factors, including regulating gas emissions within the production of coke because the coke texture is heterogeneous and is produced from different coals, the impact of the inverse relationship between coke texture and reactivity, the formation of anisotropic textures in the production coke, and their impact on the resistance properties of the production coke (**MacPhee et al., 2013; Sharma et al., 2014; Shui et al., 2011; Roest et al., 2016**).

Kimura et al. (2019) have shown that the average coke size is strongly related to the coke contraction ratio after re-freezing, both in laboratory and industrial scales. The average coke size increases with a decrease in the coke contraction ratio and increases with a reduction in the coal tar content. **Yang et al. (2018)** revealed that the M25 decreases when the percentage weight of weak

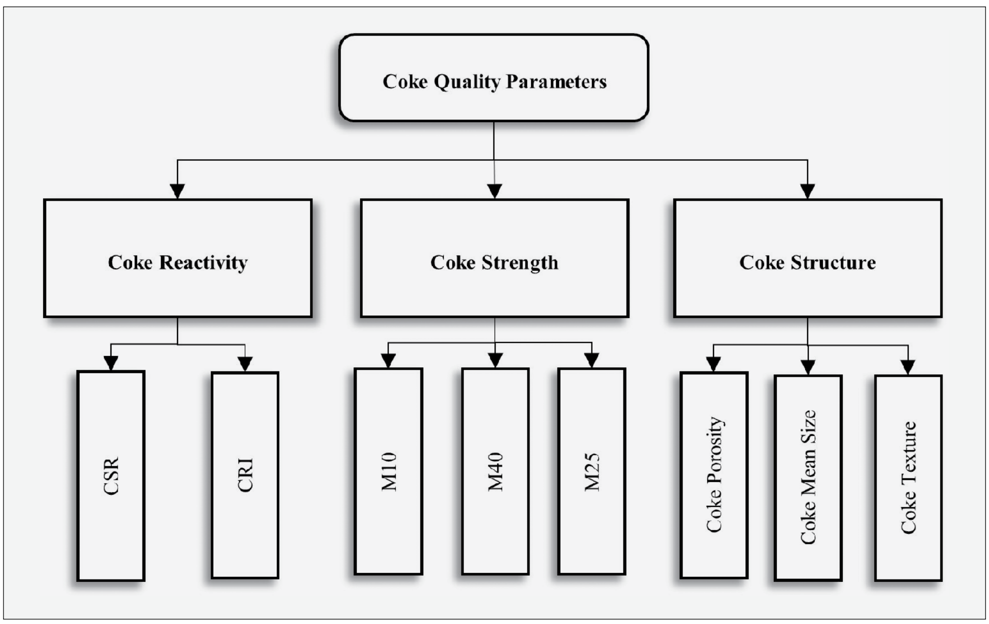


Figure 14: Coke quality parameters distribution

Table 5: Coke indexes and their relationship

+: Effective/ -: without effect/ *: Not enough information		Coke Strength			Coke Reactivity		Coke Structure		
		M10	**M25**	**M40**	**CSR**	**CRI**	**Porosity**	**Mean Size**	**Texture**
Coke Strength	M10		-	-	*	*	-	-	-
	M25	-		-	*	*	-	-	-
	M40	-	-		*	*	-	-	-
Coke Reactivity	CSR	-	-	-		+	-	-	-
	CRI	-	-	-	+		-	-	-
Coke Structure	Porosity	+	+	+	+	+		+	+
	Mean Size	+	+	+	+	+	-		-
	Texture	+	+	+	+	+	+	+	

coals in the blend increases. They found that changes in the mechanical strength of the coke are linked to the volume change of the coke. Their analysis clearly showed that the coke volume significantly increases with an increase in the fatty coal content in the coal blend. **Jha et al. (2021)** illustrated that a reduction in the percentage of fine-grained and high-ash coals in the mix increases the apparent density of the furnace, leading to an enhancement in CSR and the improvement of coke strength indices **(M10 and M40)**. **Zhang et al. (2022)** demonstrated that the Optical Texture index of Coke (OTIC) increases with the rise in carbon content of coke. Their analysis indicated that as OTIC increases, the CRI value decreases, while CSR and M25 values increase. **Nyathi et al. (2013)** showed that an increase in the furnace's apparent density and coke formation rate leads to an increase in CSR. Increasing the furnace's apparent density enhances the carbon phase ratio in the mix, resulting in improved carbon reactivity and reduced crystallinity of the coke.

4.2. The trend of changes in coal preparation parameters from 2001 to 2022 in selected articles

Coal preparation parameters are generally classified into two major categories in the reviewed articles: coal preparation parameters at the source (**coal washing plant**) and coal preparation parameters at the destination (**iron smelting plant**). As defined in this review article, the second category of coal preparation parameters refers to the coal preparation parameters at the destination (iron smelting plant). Based on the analysis of the selected articles, the most significant ones are: coal mixture, coal stamping, coal moisture, coal caking properties, coal bulk density, percentage of coal additives, and coal particle size (**Nag et al., 2009; Kumar et al., 2022; Ravichandar et al., 2016; Sakurovs & Burke, 2011; Casal et al., 2003**).

According to the statistical analysis of these parameters in the articles, coal blends were found to be a significant factor in all of them **Figure 9**. There has been more attention paid to the blend of coal, additives added to coal in the coking plant, the caking properties of coal, and the bulk density of coal in the articles. As shown in the chart below, in the period from 2001 to 2022, coal mixture has been investigated in the majority of articles, either as a primary focus or as one of the parameters that affects other parameters (see **Figure 15)**.

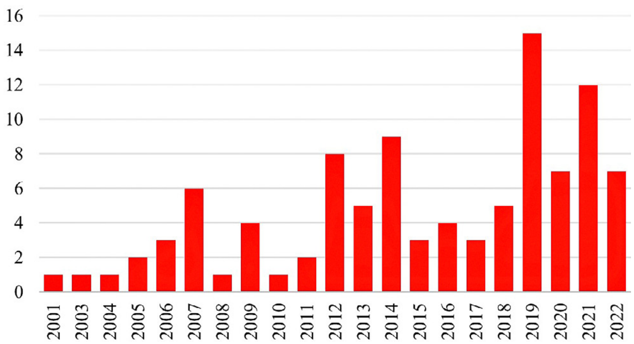


Figure 15: Percentage of coal blend examinations in selected articles by year

The experiments conducted in **Prasad et al. (2001)** revealed that high-ranking coals with high volatile matter content contribute to increased coke strength, likely due to the presence of a significant amount of fusinite in the coals. **Sun et al. (2019)** demonstrated that the pressure of coke formation has a complex relationship with the structure of the coal blend used. Increasing moisture in the blend increases the average pressure flow, while dry and wet coal blends can significantly decrease the pressure of coke formation. The findings from **Nomura et al. (2004)** indicated that the apparent density of dry coal can control the pressure of coke formation by regulating the blending ratio of low-ranked coals in the mix. This regulation is achieved through adjusting the overall coal expansion in the mixture. Analyses by **Sharma et al. (2007)** confirmed that the metallurgical coke quality is significantly dependent on the type of coal, as well as the physical and chemical properties of the coal, including granulometry and their thermochemical behavior.

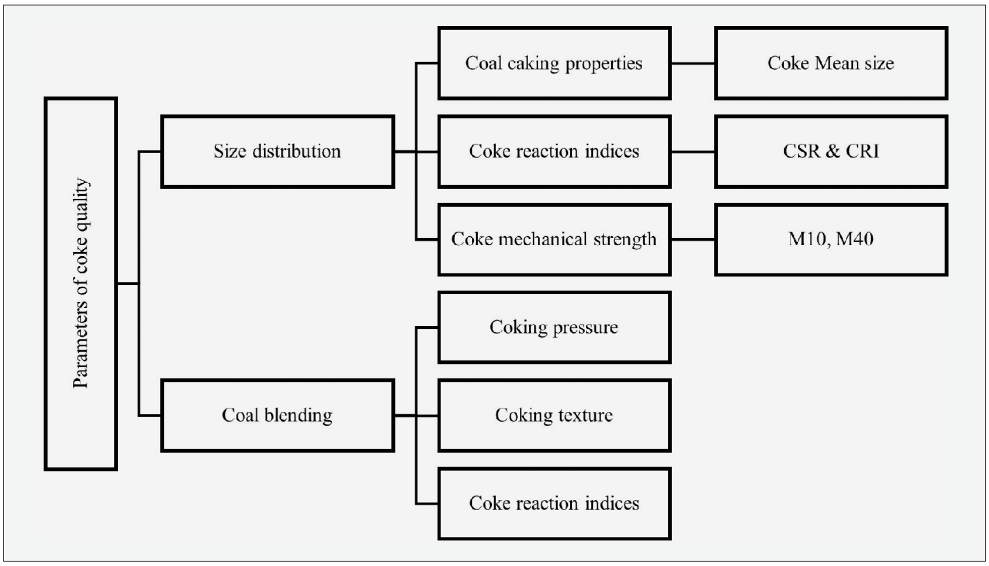


Figure 16: Parameters of coke quality

4.3. The most important parameters of coke quality in the reviewed articles considering the impact of coal size distribution and coal blend

Based on a review of the articles, it was found that coal's size distribution was less investigated than coal mixture's size distribution, as shown in **Figure 9**. Despite these limited studies, it has been revealed that the size distribution and composition of coal directly influence many of the properties of the produced coke, as shown in **Figure 16**.

It was found that size distribution directly affects coal caking properties, average size and coke reaction indices (**Yang et al., 2018**). By properly distributing the size of coal particles in the coking feed, the gap between the particles can be reduced and the composition of the particles will be more uniform (**Zhang et al., 2019**). By doing so, it is possible to improve coke's caking properties, increase its mechanical strength, cold strength, and thermal resistance (**Jha et al., 2021**). Furthermore, increasing the size distribution of coal particles tends to increase the load density and decrease the form of the particles when fitted together. Coke's caking properties and mechanical resistance may be adversely affected by this issue. According to research, a more uniform distribution of coal particle sizes in a mixture may result in a decrease in CRI and an increase in CSR (**Lyalyuk et al., 2013; Sharma et al., 2005; Nomura, 2016; Saito et al., 2014; Suopajärvi et al., 2017; Abel et al., 2009**).

In the study by **Burat et al. (2015)** coarse coal was found to have the highest compressive strength in the mixture, resulting in a decrease in the strength of the coke that was produced. This study confirmed that coarse particles reduce the cold mechanical strength, coke reactivity, and post-reaction strength of coke. The coal mixture may also have a direct effect on the reaction and resistance indicators, as well as the coking pressure and texture of the coke (**Sun et al., 2019; North et al., 2019**). Coal mixtures can affect coke's mechanical strength. The mechanical strength of coke can be affected by coals with different degrees of sintering and carbon contents (**Tiwari et al., 2014; Ghosh et al., 2022; Rejdak et al., 2021**).

The melting point of coke is one of the factors that are affected by coal mixtures when determining the quality of coke. Coke melting point is affected by its chemical composition and proportion of coals. By mixing coals with different melting points in an appropriate ratio, it is possible to produce coke with a higher melting point (**Liu et al., 2018; Zelenskii et al., 2018**). Coke's texture is also affected by coal mixtures. As a result of pollutants and impurities in the coal used to make the coke, side phases such as clinkers can form, causing the texture of the coke to be uneven and thus affecting the mechanical properties of the coke (**Yang et al., 2019**).

4.4. Predicting the future research aspects for coke quality parameters

A study of the changes in the research interests of researchers in the field of coking and an analysis of the recommendations presented in articles revealed that, due to the dispersion of the coke industry, the various companies that produce and consume coke, and the different standards that are used in different countries to determine the quality of coke, it is impossible to determine the future direction of this industry with any accuracy. Nevertheless, this study demonstrated that the significance of the coking process, seen from three overarching perspectives of producers, consumers, and researchers in the coke domain, has been examined in 118 selected articles, as shown in **Figure 17**.

It was revealed that articles in the field of coking are summarized into three sections: before the initiation of

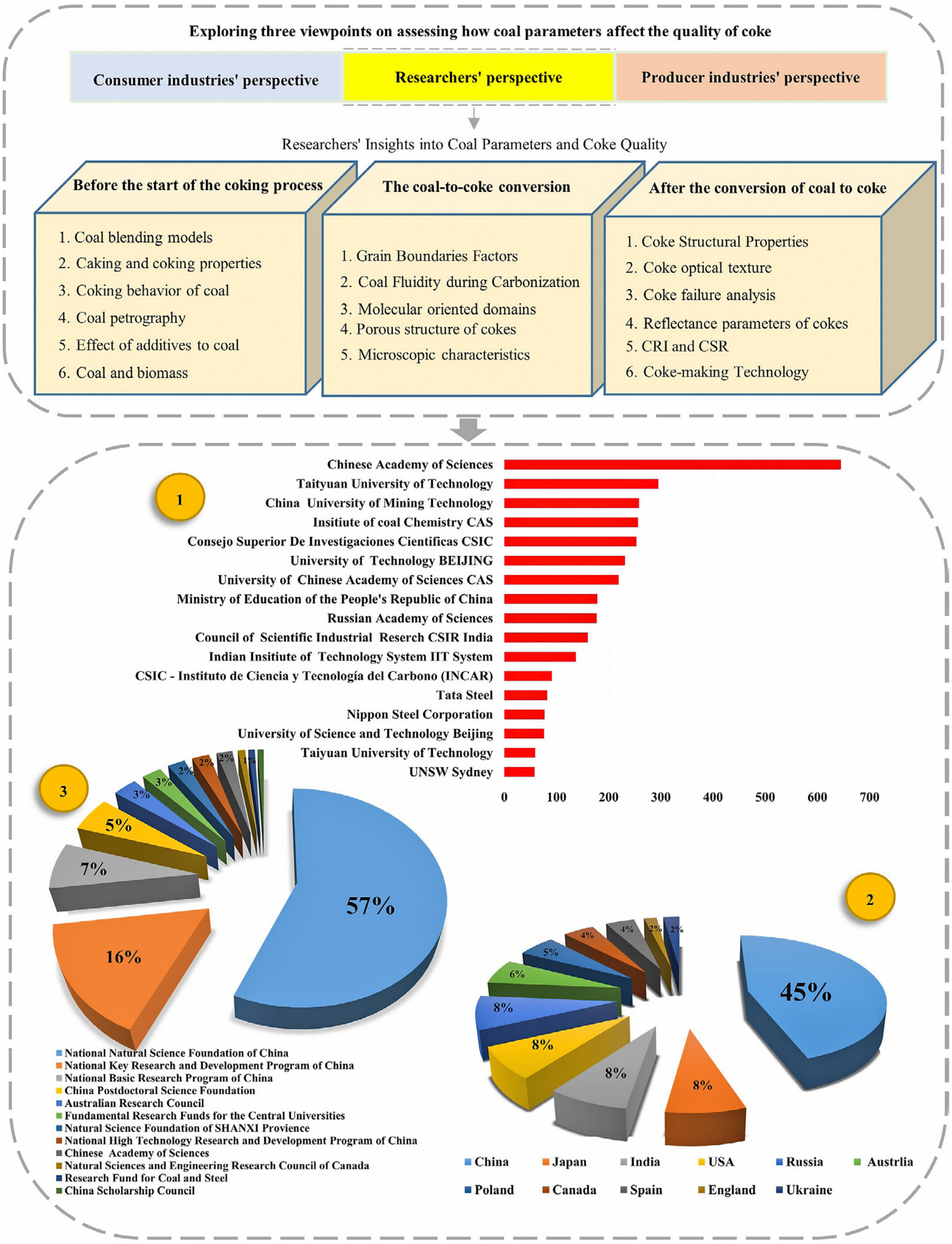


Figure 17: Summary of the present article

the coking process, during the conversion of coal to coke, and after the conversion of coal to coke. Interestingly, the "most cited" articles, based on the number of citations in journals Fuel and Fuel Processing Technology, have been published abundantly; this is also evident in the frequency of published articles. By examining the content of the articles, it became clear that the most interesting topics in the field of cake making that have been studied by authors between the years 2001 and 2022 are the same as those presented in the three boxes in **Figure 17**. An examination of the dependency, country of publication, and sponsoring entities of the articles revealed that the top institutions, publishing countries, and transient capital companies in the coking domain are as follows 1, 2, and 3, as shown in **Figure 17**:

- Chinese Academy of Sciences,
- China,
- National Natural Science Foundation of China.

Out of approximately 4000 published articles on the subject of coal and coke in databases 1 and 2, around 45% have been from China; among these articles, about 20% of them have been submitted with the affiliation of the Chinese Academy of Sciences. Among the submitted articles from China, over 50% have been financially supported by the National Natural Science Foundation of

China. Analysing the article content and focusing on the suggestions presented in articles indicated that the future focus of articles will be dedicated to the following sections:

- Identifying and improving the quality of coke using laboratory-scale experiments, such as examining the structure and characteristics of coal pyrolysis and focusing on improving coke quality, in response to the needs of industries that use coke,
- Enhancing coal quality at the source, including reducing levels of harmful substances in coal (ash and sulphur content),
- Using more environmental standards when discussing coking on an industrial scale, such as using biomass as an industrial component of the coking process; removal, refining, and consuming produced gases.

4.5. Results, discussion, and recommendations

A literature review conducted independently can assist professionals in identifying accurate and reliable evidence about a particular topic for the purpose of making decisions and providing direction (**Fisch & Block, 2018**). A systematic review of the literature can, however, increase the quality, reliability, reproducibility, and validity of the subjects under review. Accordingly, the current research interest in coking is a result of the observation that the potential role of coal preparation parameters on coke quality has been largely neglected in previous studies. Hence, the present study aimed to clarify the role and effect of coal preparation parameters on coke quality. A thorough review of the published literature in the field of coking over the last 20 years was conducted in three stages, using the Scopus and WOS databases:

- Determining the review process: The study was a systematic review conducted according to the PRISMA standard, with a clear progression following (see **Figure 1**).
- Quantitative analysis of literature: This study examined and analysed 118 articles from literature by examining the title, abstract, methodology, and conclusion, with the assistance of experts.
- In the qualitative analysis of literature, a rigorous process involving a systematic review led to the selection of 118 articles for in-depth examination. This scrutiny was carried out using a tried and tested research methodology based on expert knowledge. Moreover, a comprehensive scientometric evaluation was performed to provide a holistic view of the present landscape and emerging patterns in the area of coking. The assessment delved into various aspects, including the annual volume of publications, key sources shaping the discourse, notable authors driving innovation, patterns of international collaboration, and identification of articles garnering significant citations.

Quantitative analysis of the research results showed that most of the studies (47%) focused on the problem of coal blending as a key factor in improving the quality of coke. Coke resistance was examined in 27% of the articles included in the review of the coking process. Upon analysis of the articles, it was discovered that (roughly 43%) of the literature on coking came from only two countries, India and China. The analysis of bibliometrics data and scientific mapping tools was conducted in this research to identify important research topics in the field of coke-making, which included:

- Investigating the effect of coking conditions on coke quality,
- Examining the effects of coal properties on the quality of coke,
- Investigating production coke properties (resistance, reactive properties of coke and coke structure),
- Performing simulations of coal converting to coke and coke during combustion,
- Improvement of coke quality through modelling the coal mixing process.

The review of the selected articles indicated that the researchers focused too much on two different parts of the coking process, i.e. the role of coking before and after coking. This case has resulted in a lack of attention being paid to the time frame during which coal is converted to coke. In contrast, using the coking process in its traditional form has led to significant gaps and challenges in the field of coking, including:

- Lack of comprehensive studies to evaluate boundary conditions in all stages of coal, coal coke, and coke (apart from case studies and examinations of specific coals).
- Excessive reliance on past work and repetitive methods in conducting the studies.
- Inadequate references and descriptions of specific procedures and standards in the coking process in the reviewed articles from various countries.
- Emphasis on the quality features of coke without considering their interactions with each other.
- Failure to present a comprehensive and specific method for predicting the resistance and reactive indicators of coke using the intrinsic properties of coal.
- Neglecting global and comprehensive models in discussing the properties of produced coke (as in the case of points CSR and CRI in the past).

The purpose of this study was to gain valuable insight into the shortcomings of studies conducted in the field of coke-making. Researchers interested in conducting research in coke-making are recommended to focus more on the gaps and challenges mentioned in the previous section and consider the aspects highlighted above. For those researchers aiming to publish research articles in coke-making, it is advised to concentrate on determining the type and degree of interaction between the two quality parameters of coke (CRI and CSR) and refrain from investigating the impact of intrinsic coal properties on their coke quality indicators since many researchers have explored these topics before. As for researchers intending to write a comprehensive review on coke-making, it is recommended to study various review articles before starting work as this will be highly beneficial in gaining insight for writing both traditional and systematic review articles. Considering the breadth of the field of coke-making, which has its roots in recent centuries, reviewing all published works in a literature review is impossible. Therefore, in future research, it is better to use other approaches such as meta-analysis or bibliometric review using various software tools. Another method is for researchers to use combinations of other keywords with each other or different keywords instead of using keyword pairs as shown in **Table 1**. While examining literature may not cover all possible keyword combinations, other keyword combinations may provide further insight.

5. Conclusion

Using a systematic review of academic studies in the field of coking, the current study investigates the effects of coal preparation parameters on the quality of coke. This research aims to determine the effects of coal preparation parameters on coke quality by determining 3 main objectives, 4 research questions, and selecting 118 articles from 7 different sections within the field of coke. Four research gaps were identified, based on which future research suggestions were made. The study revealed that coking is an important strategic process in the field of steel production that is still of interest to researchers due to its role in maintaining the stability of consumption markets. There has been an increase in articles in various periods, indicating that all periods have witnessed an increase in interest in different aspects of coking. As a result of these factors, the effect of coal mixture on coke quality accounted for the highest frequency of reviews in articles (47%). Due to the fact that coking is a process that requires updates in production conditions and consumption mixtures in order to achieve better performance and power. Therefore, the improvement of these two can act as a beneficial mechanism in the production process. Developing a consensus between technical conditions and production factors, as well as changing the managerial vision, can assist policy makers in improving and creating sustainable production mechanisms in the steel industry.

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SAŽETAK

Istraživanje odnosa između intrinzičnih svojstava, parametara pripreme ugljena i kvalitete koksa: sustavni pregled literature

Svrha je ove studije prikazati neke od ključnih istraživačkih koncepata vezanih uz metalurški koks. Kako se razvijalo istraživanje prostora gdje se vade sirovine za metaluršku proizvodnju koksa, istraživači su sve više pokazivali interes za učinke intrinzičnih svojstava ugljena, parametara pripreme ugljena i tehnoloških uvjeta proizvodnje koksa na kvalitetu metalurškoga koksa. U ovome pregledu znanstvene literature korišteni su specifični protokoli, analiza sadržaja i tematsko kodiranje slučajeva prema smjernicama Preferencijalnoga izvještaja za sustavni pregled i metaanalizu (PRISMA – *Preferred Reporting Items for Systematic Review and Meta-Analyses*) kako bi se istražio istovremeni učinak parametara na kvalitetu koksa. Proveden je pregled 118 znanstvenih članaka, koji je uključivao analizu njihovih sažetaka, uvoda, metodologije i rezultata. Prema rezultatima ove studije mješavine ugljena i veličina čestica ugljena imaju izravan učinak na mehanička svojstva koksa, teksturu koksa i reaktivna svojstva koksa. Pregledom raznih članaka pokazalo se da prisutnost masnih ugljena s manjom distribucijom čestica, u kombinaciji s većim slabim ugljenima, dovodi do stvaranja jače strukture u proizvedenome koksu. Međutim, to ne jamči poboljšanje parametara reaktivnosti koksa. S druge strane, povećanjem omjera miješanja ugljena za koksiranje u konačnoj smjesi za proizvodnju koksa normalne veličine (dimenzija manjih od 3 mm) poboljšavaju se parametri reaktivnosti koksa. Studije koje istražuju strukturu koksa pokazale su da je kohezivna mozaična struktura visokokvalitetnoga koksa rezultat dobre raspoređenosti maceralnih mješavina ugljena za koksiranje s optimalnom raspodjelom veličine čestica kod ostalih ugljena.

Ključne riječi:
priprema ugljena, kvaliteta koksa, proizvodnja koksa, sustavni pregled literature

Author's contribution

MohammadReza Ameri Siahuei (1) (Ph.D. Candidate): Compiler of all articles, author of the complete manuscript, and implementer of the research concept. **Mohammad Ataei (2)** (Professor): Idea generator and supervisor on the review section related to the preparation parameters for coal. **Farhang Sereshki (3)** (Professor): Idea generator and supervisor on the drafting section related to the behaviour of coal during carbonization.