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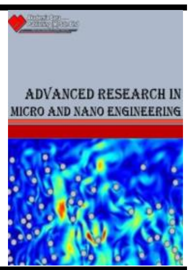

Correlation Between Computational Fluid Dynamics (CFD) and Nanotechnology

Nor Azwadi Che Sidik[1], Dwi Fitria Al Husaeni[1], Asep Bayu Dani Nandiyanto[1,*]

[1] Universitas Pendidikan Indonesia, Bandung, Indonesia

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ABSTRACT

This research aims to find the relationship between Computational Fluid Dynamics (CFD) and nanotechnology and carry out bibliometric analysis to determine research trends in CFD and nanotechnology. This research used bibliometric analysis methods. The keywords used are "Computational Fluid Dynamics (CFD)" and "Nanotechnology". The data processing and analysis are carried out quantitatively based on the principles of bibliometric analysis. The search results show that the year range for research publication articles on CFD and Nanotechnology used is from 2001 - 2024 with a total of 193 documents. The results of this research show that the relationship between CFD and nanotechnology is very close. This is because CFD provides an important tool for understanding, designing, and optimizing various processes and devices at the nanoscale. Additionally, CFD enables faster and more efficient progress in various nanotechnology applications. Based on an analysis of research developments, the development of article publications on CFD and nanotechnology in Scopus has a tendency to increase from the beginning of 2001 to 2024. In this research, it is known that the topic of CFD has become a research trend in the period 2012 to 2019 with the highest trend in 2016. Meanwhile, the topic of nanotechnology became a research trend from 2010 to 2018 with the highest trend in 2014. This research development can be caused by significant technological and methodological advances since the Industrial Revolution 4.0 which began at the beginning of the 21st century until now. This research can be used as consideration and reference for further research which will discuss CFD and nanotechnology.

1. Introduction

Nanotechnology has emerged as a revolutionary field, offering unprecedented innovation opportunities across a wide range of scientific and industrial fields. Nanotechnology is a field of science at the nanometer scale, manipulating matter at the atomic and molecular level to create materials and devices with new properties and functions [1]. The increasingly widespread application of nanotechnology makes the need for advanced modeling techniques to understand and optimize

* *Corresponding author.*
E-mail address: nandiyanto@upi.edu

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these nanoscale phenomena. One technology that can be used for this process is Computational Fluid Dynamics (CFD).

CFD is a technology that involves numerical analysis and simulation of fluid flow, providing detailed insight into fluid behavior in complex systems [2]. CFD can be used to model and predict interactions between fluids and nanomaterials with high precision. This CFD capability is critical for a variety of applications, from designing efficient drug delivery systems using nanoparticles to developing advanced cooling mechanisms in nanoelectronics. CFD can be utilized to simulate dynamic processes at the nanoscale [3], thereby reducing reliance on expensive and time-consuming experimental methods.

Currently, there has been a lot of research discussing the use of CFD in nanotechnology. Several examples include the development of biopesticide nanotechnology [4], research on mixing systems in anaerobic digestion [5], research on the effect of nanoparticles on changing wettability to increase oil recovery [6], investigation of the effects of silica nanofluids to improve oil recovery applications [7], and research on the heating performance of large-scale channel heaters by adding synthesized carbon-nanodotites to fluid bath heaters [8]. Other reports on CFD and its correlation to nanotechnology are presented in Table 1. However, no research has yet measured the correlation or relationship between CFD and nanotechnology. Therefore, this research was carried out with the aim of finding the relationship between CFD and nanotechnology. This research was also carried out to find out the trends in CFD and nanotechnology research through bibliometric analysis. Bibliometric analysis is one of the effective research methodologies to understand current research trends. Previous studies on bibliometric analysis are shown in Table 2.

Table 1
Current reports on the correlation between CFD and nanotechnology in CFD Letters published in 2023 based on Scopus database taken in May 2024

No	Author(s)	Title	Reference
1.	Kurdistani, S.M., Perrone, G.C.	Diffusion of a Surface Marine Sewage Effluent	[9]
2.	Punitha, S., Ananthaswamy, V., Santhi, V.K.	Approximate Analytical Expression for the Influence of Flow of MHD Nanofluids on Heat and Mass Transfer	[10]
3.	Nandiyanto, A.B.D., Ragadhita, R., Aziz, M.	Involving Particle Technology in Computational Fluid Dynamics Research: A Bibliometric Analysis	[11]
4.	Mohammed, A.R., Shaik, M.S., Ravuri, M.R., Chundru, M., Gurram, D.	Thermophoresis, Brownian Diffusion, Porosity, and Magnetic Parameters' Effects on Three-Dimensional Rotating Ag-CuO/H2 O Hybrid Nanofluid Flow across a Linearly Stretched Sheet with Aligned Magnetic Field	[12]
5.	Goddubarla, G., Rao, S.K., Vajha, S.K.	MHD 3D Mixed Upper Convective Flow of Maxwell Nanofluid Flow Past in the Presence of Diffusion Thermo and Thermophoresis Effect using Nonlinear Radiative Heat Flux	[13]
6.	Abdullah, Y.M., Aziz, G.S., Salah, H.K., Sharaf, H.K.	Simulate the Rheological Behaviour of the Solar Collector by Using Computational Fluid Dynamic Approach	[14]
7.	Gopalam, N., Annareddy, S.K.	Thermal Diffusion and Diffusion Thermo Effects on MHD 3D Mixed Upper Convective Flow of Maxwell Nanofluid Flow Past using Nonlinear Radiative Heat Flux	[15]
8.	Devi, P.N.L., Meduri, P.K.	Oscillatory Flow of Couple Stress Fluid Flow over a Contaminated Fluid Sphere with Slip Condition	[16]
9.	Jaffrullah, S., Sridhar, W., Ganesh, G.R.	MHD Radiative Casson Fluid Flow through Forchheimer Permeable Medium with Joule Heating Influence	[17]
10.	Ishak, S.S., Azhar, N.N.M.N., Nazli, N.S., …Kasim, A.R.M., Mohammad, N.F.	Carbon Nanotubes Flow on Mixed Convection of Aligned Magnetohydrodynamics over a Static/Moving Wedge with Convective Boundary Conditions	[18]

11.	Sekhar, P.R., Sreedhar, S., Ibrahim, S.M., Kumar, P.V.	Radiative Heat Source Fluid Flow of MHD Casson Nanofluid over A Non-Linear Inclined Surface with Soret and Dufour Effects	[19]
12.	Sandhya Rani, K., Venkata Ramana Reddy, G., Oke, A.S.	Significance of Cattaneo-Christov Heat Flux on Chemically Reacting Nanofluids Flow Past a Stretching Sheet with Joule Heating Effect	[20]
13.	Zukri, N.Z.M., Ilias, M.R., Ishak, S.S., …Makhatar, N.A.M., Rahman, M.N.A.	Magnetohydrodynamic Effect in Mixed Convection Casson Hybrid Nanofluids Flow and Heat Transfer over a Moving Vertical Plate	[21]
14.	Abuiyada, A., Eldabe, N., Abouzeid, M., Elshaboury, S.	Influence of Both Ohmic Dissipation and Activation Energy on Peristaltic Transport of Jeffery Nanofluid through a Porous Media	[22]
15.	Mishra, J., Samantara, T.	Effect of Radiation and Non-Uniform Heat Source/Sink on Flow over a Linear Stretching Sheet with Fluid Particle Suspension	[23]
16.	Fayadh, S.B., Khalil, W.H., Dawood, H.K.	Numerical Study on the Effect of Using CuO-Water Nano fluid as a Heat Transfer Fluid on the Performance of the Parabolic Trough Solar Collector	[24]
17.	Zainal, N.A., Naganthran, K., Nazar, R.	Stability Analysis of Unsteady Mixed Convection Flow Near the Stagnation Point with Buoyancy Effect	[25]
18.	Qader, F.F., Hussein, A.M., Danook, S.H., Mohamad, B., Khaleel, O.S.	Enhancement of Double-Pipe Heat Exchanger Effectiveness by Using Porous Media and TiO2 Water	[26]
19.	Azmi, W.F.W., Mohamad, A.Q., Jiann, L.Y., Shafie, S.	Free Convection Caputo-Fabrizio Casson Blood Flow in the Cylinder with Slip Velocity	[27]
20.	Mugisidi, D., Fajar, B., Syaiful, S., Utomo, T.	Solar Still with an Integrated Conical Condenser	[28]
21.	Saupi, S., Ghani, A.A., Arifin, N.M., Rosali, H., Wahid, N.S.	An Exact Solution of MHD Hybrid Nano fluid over a Stretching Surface Embedded in Porous Medium in the Presence of Thermal Radiation and Slip with Suction	[29]
22.	Bali, R., Prasad, B.	Study of Nanoparticle Diffusion in Capillary-Tissue Exchange System using Jeffrey Nanofluid Model: Effects of Shapes of Nanoparticles	[30]
23.	Rosli, W.M.H.W., Mohamed, M.K.A., Sarif, N.M., Mohammad, N.F., Soid, S.K.	Boundary Layer Flow of Williamson Hybrid Ferrofluid over A Permeable Stretching Sheet with Thermal Radiation Effects	[31]
24.	Jaafar, A., Yusof, Z.M., Ahmad, N., Jamaludin, A.	The Effects of Buoyancy, Magnetic Field and Thermal Radiation on the Flow and Heat Transfer due to an Exponentially Stretching Sheet	[32]
25.	Bakar, F.N.A., Soid, S.K.	MHD Stagnation-Point Flow and Heat Transfer in a Micropolar Fluid over an Exponentially Vertical Sheet	[33]
26.	Arifin, N.S., Kasim, A.R.M., Zokri, S.M., Haryatie, S.F., Salleh, M.Z.	Dusty Casson Fluid Flow containing Single-Wall Carbon Nanotubes with Aligned Magnetic Field Effect over a Stretching Sheet	[34]

Table 2
Previous reports on bibliometric analysis in CFD Letters and Journal of published based on Scopus database taken in May 2024

No	Author(s)	Title	Reference
1	Muktiarni, M., Rahayu, N.I., Nurhayati, A., Bachari, A.D., Ismail, A.	Concept of Computational Fluid Dynamics Design and Analysis Tool for Food Industry: A Bibliometric	[35]
2	Rachmat, B., Agust, K., Rahayu, N.I., Muktiarni, M., Tomoliyus	Concept of Computational Fluid Dynamics and Its Application in Sport Science: Bibliometric Analysis of Modelling Thermal Comfort in Sport Hall	[36]
3	Nandiyanto, A.B.D., Ragadhita, R., Aziz, M.	Involving Particle Technology in Computational Fluid Dynamics Research: A Bibliometric Analysis	[37]

4	Laita, M., Sabbahi, R., Elbouzidi, A., …Benkirane, R., Aithaddou, H.	Effects of Sustained Deficit Irrigation on Vegetative Growth and Yield of Plum Trees Under the Semi-Arid Conditions: Experiments and Review with Bibliometric Analysis	[38]
5	Nurrahma, A.H.I., Putri, H.H., Syahadat, R.M.	Scientific Research Trends of Flooding Stress in Plant Science and Agriculture Subject Areas (1962-2021)	[39]
6	Shidiq, A.P.	A Bibliometric Analysis of Nano Metal-Organic Frameworks Synthesis Research in Medical Science Using VOSviewer	[40]
7	Ramadhan, D.F., Fabian, A.M., Saputra, H.M.	Dental Suction Aerosol: Bibliometric Analysis	[41]
8	Kumar, K.	Mapping of Nanotechnology Research in Animal Science: Scientometric Analysis	[42]
9	Angraini, L.M., Susilawati, A., Noto, M.S., Wahyuni, R., Andrian, D.	Augmented Reality for Cultivating Computational Thinking Skills in Mathematics Completed with Literature Review, Bibliometrics, and Experiments for Students	[43]
10	Mardina, P., Wijayanti, H., Juwita, R., …Rawei, O.K., Lestari, L.	Corncob-Derived Sulfonated Magnetic Solid Catalyst Synthesis as Heterogeneous Catalyst in The Esterification of Waste Cooking Oil and Bibliometric Analysis	[44]
11	Solihah, P.A., Kaniawati, I., Samsudin, A., Riandi, R.	Prototype of Greenhouse Effect for Improving Problem-Solving Skills in Science, Technology, Engineering, and Mathematics (STEM)-Education for Sustainable Development (ESD): Literature Review, Bibliometric, and Experiment	[45]
12	Yang, W., Chookhampaeng, C., Chano, J.	Spatial Visualization Ability Assessment for Analyzing Differences and Exploring Influencing Factors: Literature Review with Bibliometrics and Experiment	[46]
13	Arianingrum, R., Aznam, N., Atun, S., …Anisa, N.F., Devani, L.K.	Antiangiogenesis Activity of Indonesian Local Black Garlic (Allium Sativum 'Solo): Experiments and Bibliometric Analysis	[47]
14	Abduh, A., Mulyanah, A., Darmawati, B., …Jayadi, K., Rosmaladewi, R.	The Compleat Lextutor Application Tool for Academic and Technological Lexical Learning: Review and Bibliometric Approach	[48]
15	Rahmat, A., Sutiharni, S., Elfina, Y., …Sulistyowati, Y., Mutolib, A.	Characteristics of Tamarind Seed Biochar at Different Pyrolysis Temperatures as Waste Management Strategy: Experiments and Bibliometric Analysis	[49]
16	Hamidah, I., Ramdhani, R., Wiyono, A., …Yunas, J., Rusydi, A.	Biomass-Based Supercapacitors Electrodes for Electrical Energy Storage Systems Activated Using Chemical Activation Method: A Literature Review and Bibliometric Analysis	[50]
17	Sahidin, I., Nohong, N., Manggau, M.A., …Rahayu, N.I., Muktiarni, M.	Phytochemical Profile and Biological Activities of Ethylacetate Extract of Peanut (Arachis hypogaea L.) Stems: In-Vitro and In-Silico Studies with Bibliometric Analysis	[51]
18	Utama, D.M., Santoso, I., Hendrawan, Y., Dania, W.A.P.	Sustainable Production-Inventory Model with Multi-Material, Quality Degradation, and Probabilistic Demand: From Bibliometric Analysis to A Robust Model	[52]
19	Juhanaini, J., Tandu Bela, M.R.W.A., Rizqita, A.J., Susilawati, A.	How Eyes and Brain See Color: Definition of Color, Literature Review with Bibliometric Analysis, and Inquiry Learning Strategy for Teaching Color Changes to Student with Mild Intelligence Barriers	[53]
20	Santoso, B., Hikmawan, T., Imaniyati, N.	Management Information Systems: Bibliometric Analysis and Its Effect on Decision Making	[54]
21	Gunawan, B., Ratmono, B.M., Abdullah, A.G., Sadida, N., Kaprisma, H.	Research Mapping in the Use of Technology for Fake News Detection: Bibliometric Analysis from 2011 to 2021	[55]
22	Mudzakir, A., Rizky, K.M., Munawaroh, H.S.H., Puspitasari, D.	Oil Palm Empty Fruit Bunch Waste Pretreatment with Benzotriazolium-Based Ionic Liquids for Cellulose Conversion to Glucose: Experiments with Computational Bibliometric Analysis	[56]

23	Nandi, N., Dede, M.	Urban Heat Island Assessment using Remote Sensing Data in West Java, Indonesia: From Literature Review to Experiments and Analyses	[57]
24	Soegoto, H., Soegoto, E.S., Luckyardi, S., Rafdhi, A.A.	A Bibliometric Analysis of Management Bioenergy Research Using Vosviewer Application	[58]
25	Setiyo, M., Yuvenda, D., Samue, O.D.	The concise latest report on the advantages and disadvantages of pure biodiesel (B100) on engine performance: literature review and bibliometric analysis	[59]
26	Castiblanco, P.A., Ramirez, J.L., Rubiano, A.	Smart materials and their application in robotic hand systems: A state of the art	[60]
27	Jamaltul Nizam Shamsuddin, Christopher Gan, Dao Le Trang Anh	Bibliometric Analysis of InsurTech	[61]
28	Punithavili Mariappan, Mohd Zahuri Khairani, Norzuraina Mohd, Maran Chanthiran, Andy Noces Cubalit	Uncovering Emerging Trends in Technology and Art Education: A Bibliometric Mapping Analysis	[62]
29	Nurul Syahida Abu Bakar, Wan Fairos Wan Yaacob, Yap Bee Wah, Wan Marhaini Wan Omar, Utriweni Mukhaiyar	Visualising Current Research Trends in Class Imbalance using Clustering Approach: A Bibliometrics Analysis	[63]
30	Via Luviana Dewanty, Nuria Haristiani, Leo Sadewo, Annisa Qamara Tasman	The Use of Technology and Media in Japanese Language Learning: A Bibliometric Analysis	[64]
31	Asep Bayu Dani Nandiyanto , Dwi Fitria Al Husaeni , Dwi Novia Al Husaeni	Social Impact and Internationalization of "Indonesian Journal of Science and Technology" the Best Journal in Indonesia: A Bibliometric Analysis	[65]
32	Davin Arkan Admoko, Bambang Darmawan, A. Ana, Vina Dwiyanti	A Cluster-Based Bibliometric Analysis of the Emerging Technological Landscape in Logistics using Vosviewer	[66]
33	M. Muktiarni, Nur Indri Rahayu, Affero Ismail, Amalia Kusuma Wardani	Bibliometric Computational Mapping Analysis of Trend Metaverse in Education using VOSviewer	[67]
34	Asep Bayu Dani Nandiyanto, Dwi Novia Al Husaeni, Dwi Fitria Al Husaeni	Introducing ASEAN Journal of Science and Engineering: A Bibliometric Analysis Study	[68]
35	Arif Husein Lubis, Didin Samsudin, Risa Triarisanti, Mohammad Iqbal Jerusalem, Yoonjung Hwang	A Bibliometric Mapping Analysis of Publications on The Utilization of Artificial Intelligence Technology in Language Learning	[69]
36	Asep Bayu Dani Nandiyanto, Dwi Novia Al Husaeni, Dwi Fitria Al Husaeni, Ida Hamidah, Bunyamin Maftuh, M. Solehuddin	Is Universitas Pendidikan Indonesia Ready for Internationalization? A Bibliometric Analysis in The Science and Technology-Related Publications	[70]
37	Asep Bayu Dani Nandiyanto, Dwi Fitria Al Husaeni, Dwi Novia Al Husaeni	Introducing ASEAN Journal for Science and Engineering in Materials: Bibliometric Analysis	[71]

2. Method

This research used bibliometric analysis methods. Research data was collected via the Scopus page starting on May 8 2024. The keywords used were "Computational Fluid Dynamics (CFD)" and "Nanotechnology". The search syntax on the Scopus page: (TITLE-ABS-KEY (CFD) AND TITLE-ABS-KEY (nanotechnology)) AND (LIMIT TO (LANGUAGE, "English")). The syntax has an explanation that keywords are entered based on the title and abstract of the article and the language limit of the article is limited to only English language articles. After the process of searching and retrieving research data has been successfully carried out, the next stage is quantitative data processing and analysis based on the principles of bibliometric analysis. The data visualization process was also carried out in this research. The data visualization process is carried out using Excel as a number and graph processing tool and the VOSviewer application as a tool for mapping research terms on the topics raised based on research bibliometric data. Detailed information for the use of bibliometric is explained elsewhere [72].

3. Result and Discussion

3.1 Computational Fluid Dynamics (CFD)

CFD is the analysis of systems involving fluid flow, heat transfer, and other related phenomena such as chemical reactions using computer simulations [73]. CFD has been well-reported in various areas. Examples of the CFD research published in CFD letters are presented in Table 3.

Table 3
Previous reports on CFD research published in CFD letter in 2024 based on Scopus database taken in May 2024

No	Author(s)	Title	Reference
1	Uday A. Alturfi , Abdul-Hassan K. Shukur	Investigation of Energy Dissipation for Different Breakwater Based on Computational Fluid Dynamic Model	[74]
2	Diyar F. Hussein, Yaser Alaiwi	Efficiency Improvement of Double Pipe Heat Exchanger by using TiO2/water Nanofluid	[75]
3	Blandy Berenice Pamplona Solis, Julio César Cruz Argüello, Isaias May Canche, Leopoldo Gómez Barba, Mayra Polett Gurrola	CFD Analysis in the Mesh Modified Gas Diffusion Layer of a Proton Exchange Membrane Fuel Cell (PEMFC)	[76]
4	Nguyen Van Dung, Nguyen Minh Phu	A comparative numerical study of three similar passive solar stills: Single slope, V-type, and greenhouse	[77]
5	Cristian Cardona Mancilla, Jorge Sierra Del Rio, Alejandro Ruiz Sánchez, Edwin Correa Quintana, Carlos Arrieta González, Mario Luna Del Risco	Structural Analysis of a First, Second and Third Generation Horizontal Axis Hydrokinetic Turbine	[78]
6	Sigit Purwanto, Bayu Novariawan, Suparman, Palupi Tri Widiyanti, Isnaini Pratiwiningrum, Fitri Nur Kayati	CFD Analysis and Development of Mixing Tank Design for The Fermented Starch Production Process	[79]
7	Arif Winarno, Agung Sugeng Widodo, Gatot Ciptadi, Atiek Iriany	The The Effect of Sail Layout on Fishing Vessels Hydrodynamics in The North Coast of Java Using Computational Fluids Dynamic	[80]
8	Ridzwan Kamaruddin, Syabillah Sulaiman, Amir Khalid, Mr. Arafat, Norrizam Jaat, Shaiful Fadzil Zainal Abidin, Norirda Mohamed, Mohd Fuad Yasak	Computational Fluid Dynamics: Flow Analysis on The Effect of Different Jet Orifice Angle Multi Circular Jet for Fuel and Air Mixing	[81]
9	Yaghthiswara Seran, Muhamad Safwan Muhamad Azmi, Abdul Halim Ismail, Kamarulzaman Kamarudin, Lam Chee Kiang, Norasmadi Abdul Rahim, Wan Mohd Nooriman Wan Yahya, Tan Kian Yew, Lum Wei Min	CFD Analysis of Pure Waterjet Nozzle for Fruit Peeling and Cutting Process	[82]
10	Tung Pham Duy, Tomoaki Watanabe, Koji Nagata	LES Investigation of a Piston-driven Synthetic Jet Actuator with Multiple Orifices	[83]

The CFD method covers phenomena related to fluid flow such as two-phase liquid systems, mass and heat transfer, chemical reactions, gas dispersion or the movement of suspended particles. In general, the CFD framework includes the formulation of applicable transport equations, the formulation of appropriate boundary conditions, the selection or development of computational codes to implement the numerical techniques used.

A CFD code is composed of numerical algorithms that can solve fluid flow problems. A CFD code consists of three main elements, namely pre-processor, solver, and post processor [84]. Pre-processing involves inputting the flow problem into a CFD program and transforming that input into a form suitable for use by the solver. The steps in the pre-processor stage are defining the geometry being analyzed. Then, grid generation is the division of the domain area into smaller parts that do not overlap. After that, select the physical phenomena that need to be modeled. Next, defining fluid properties, selecting boundary conditions in the control volume or cells that coincide with domain boundaries, solving flow problems (speed, pressure, temperature, etc.) which are defined at nodal points in each cell, and determining the accuracy of the CFD solution by the number of cells in the grid.

Solvers can be divided into three types, namely finite difference, finite element, finite volume and spectral methods. In general, the numerical solver method consists of the following steps, (i) predicting unknown flow variables using simple functions, (ii) discretization by substituting these predictions into the main flow equations that apply and then carrying out manipulations, mathematics, and (iii) solving algebraic equations.

Post-processing is the visualization stage of the results of the previous stage. Post-processors are increasingly developing with the advancement of engineering workstations which have quite large graphics and visualization capabilities. These visualization tools include geometry and display domains, vector plots, contour plots, 2D and 3D surface plots, display manipulation (translation, rotation, scale, etc.), and dynamic display animation results.

3.2 Nanotechnology

The ability to manipulate a material's size from large to nanoscale is the broad definition of nanotechnology [85]. The most advanced area of materials science study at the moment is nanotechnology. One topic that receives a lot of attention in nanotechnology is nanoparticles. Nanotechnology is a technology that measures using nanometer units [86]. Materials made with nanotechnology range in size from 1-100 to 1,000 nm [87]. In nanotechnology-based processes, nanoparticle synthesis can be carried out in two ways. The top-down method forms nanoparticles at the nanoscale by breaking the particles apart. And, the bottom-up method forms nanoparticles by arranging the atoms of certain compounds.

Basically, nanotechnology is the extension of existing sciences to the nanoscale. One of the most significant characteristics of the nanoscale is that the smaller object results in a greater ratio between surface area and volume. The simplest experiments that can understand the effect of size are adsorption and mechanical strength. Examples of experiments regarding the effect of size on adsorption are shown in Table 4, while that on the mechanical properties is shown in Table 5.

Table 4
Previous reports on adsorption as the function of size based on Scopus database taken in May 2024

No	Author(s)	Title	Reference
1	Nandiyanto, A.B.D., Nugraha, W.C., Yustia, I., (...), Meirinawati, H., Wulan, D.R.	Isotherm and kinetic adsorption of rice husk particles as a model adsorbent for solving issues in the sustainable gold mining environment from mercury leaching	[88]
2	Nandiyanto, A.B.D., Fiandini, M., Ragadhita, R., Aziz, M.	How to Purify and Experiment with Dye Adsorption using Carbon: Step-by-Step Procedure from Carbon Conversion from Agricultural Biomass to Concentration Measurement Using UV Vis Spectroscopy	[89]
3	Nandiyanto, A.B.D., Fiandini, M., Ragadhita, R., (...), Yunas, J., Bilad, M.R.	Sustainable Biochar Carbon Biosorbent Based on Tamarind (Tamarindusindica L) Seed: Literature Review, Preparation, and Adsorption Isotherm	[90]
4	Nandiyanto, A.B.D., Nugraha, W.C., Yustia, I., (...), Saleh, M., Ningwulan, D.R.	Rice Husk for Adsorbing Dyes in Wastewater: Literature Review of Agricultural Waste Adsorbent, Preparation of Rice Husk Particles, Particle Size on Adsorption Characteristics with Mechanism and Adsorption Isotherm	[91]
5	Nandiyanto, A.B.D., Fiandini, M., Fadiah, D.A., (...), Yunas, J., Mahdi Al Obaidi, A.Sh.	Sustainable Biochar Carbon Microparticles Based on Mangosteen Peel as Biosorbent for Dye Removal: Theoretical Review, Modelling, and Adsorption Isotherm Characteristics	[92]
6	Nandiyanto, A.B.D., Al Husaeni, D.F., Ragadhita, R., (...), Maryanti, R., Al Husaeni, D.N.	Computational calculation of adsorption isotherm characteristics of carbon microparticles prepared from mango seed waste to support sustainable development goals (SDGS)	[93]
7	Dani Nandiyanto, A.B., Al Husaeni, D.N., Ragadhita, R., (...), Al Husaeni, D.F., Maryanti, R.	Analysis of adsorption isotherm characteristics for removing curcumin dyes from aqueous solutions using avocado seed waste carbon microparticles accompanied by computational calculations	[94]
8	Dani Nandiyanto, A.B., Fiandini, M., Ragadhita, R., (...), Al Husaeni, D.F., Al Husaeni, D.N.	Removal of curcumin dyes from aqueous solutions using carbon microparticles from jackfruit seeds by batch adsorption experiment	[95]
9	Nandiyanto, A.B.D., Ragadhita, R., Fiandini, M., Maryanti, R.	Curcumin dye adsorption in aqueous solution by carbon-based date palm seed: Preparation, characterization, and isotherm adsorption	[96]
10	Ragadhita, R., Amalliya, A., Nuryandi, S., (...), Istadi, I., Al-Obaidi, A.S.M.	Sustainable Carbon-Based Biosorbent Particles from Papaya Seed Waste: Preparation and Adsorption isotherm	[97]
11	Nandiyanto, A.B.D., Hofifah, S.N., Ragadhita, R.	Adsorption isotherm analysis of floating composite zinc imidazole framework-8 in millimeter epoxy cubes	[98]
12	Nandiyanto, A.B.D., Putri, S.R., Anggraeni, S., Kurniwan, T.	Isotherm adsorption of 3000-µm natural zeolite	[99]
13	Nandiyanto, A.B., Azizah, N.N., Taufik, R.S.R.	Investigation of adsorption performance of calcium carbonate microparticles prepared from eggshells waste	[100]
14	Ragadhita, R., Nandiyanto, A.B.D.	Curcumin adsorption on zinc imidazole framework-8 particles: isotherm adsorption using langmuir, freundlich, temkin, and dubinin-radushkevich models	[101]
15	Nandiyanto, A.B.D., Hofifah, S.N., Anggraeni, S., Kurniwan, T.	Isotherm adsorption of 40-µm zeolite particles for treatment of dye wastewater	[102]

Table 5
Previous reports on mechanical properties as the function of size based on Scopus database taken in May 2024

No	Author(s)	Title	Reference
1	Nandiyanto, A.B.D., Fitriani, A.F., Pradana, R.A., (...), Azzaoui, K., Piantari, E.	Green Innovation in Brake Pad Production: Harnessing Teak Powder and Clamshells as Sustainable Alternatives for Subtractive Residual Waste to Support Sustainable Development Goals (SDGs)	[103]
2	Meziane, H., Laita, M., Azzaoui, K., (...), Siaj, M., Touzani, R.	Nanocellulose fibers: A Review of Preparation Methods, Characterization Techniques, and Reinforcement Applications	[104]
3	Ragadhita, R., Fiandini, M., Nofiani, R., (...), Nugraha, W.C., Istadi, I.	Biomass composition (cassava starch and banana (musa sp.) peels) on mechanical and biodegradability properties of bioplastics for supporting sustainable development goals (SDGS)	[105]
4	Hidayat, D.S., Rakhmat, C., Suryadi, A., (...), Nandiyanto, A.B.D., Maryanti, R.	Utilization of cornflour particles as a model for thermal insulator for supporting teaching and learning process for students with hearing impairments	[106]
5	Nandiyanto, A.B.D., Ragadhita, R., Hofifah, S.N., (...), Darmawan, A., Aziz, M.	Progress in the utilization of water hyacinth as effective biomass material	[107]
6	Nandiyanto, A.B.D., Fatimah, S., Ragadhita, R., Husaeni, D.N.A.	Particle size and pore size of rice husk ash on the resin-based brake pads performance: experiments and bibliometric literature review	[108]
7	Anggraeni, S., Nandiyanto, A.B.D., Ragadhita, R., (...), Valensia, Setiadi, D.P.	Teaching the concept of brake pads based on composites of palm fronds and rice husks to high school students	[109]
8	Nandiyanto, A.B.D., Putri, S.R., Kurniawan, T.	Natural zeolite as the reinforcement for resin-based brake pad using dual particle size	[110]
9	Anggraeni, S., Nandiyanto, A.B.D., Ainisyifa, Z.N., (...), Al Husaeni, D.F., Siswanto, A.	The effect of addition of rubbing ash and corncob ash biomass on the mechanical properties of paving blocks	[111]
10	Anggraeni, S., Anshar, A.N., Maulana, A., (...), Putri, S.R., Nandiyanto, A.B.D.	Mechanical properties of sawdust and rice husk brake pads with variation of composition and particle size	[112]
11	Nandiyanto, A.B.D., Azizah, N.N., Girsang, G.C.S.	Optimal Design and Techno-economic Analysis for Corncob Particles Briquettes: A Literature Review of the Utilization of Agricultural Waste and Analysis Calculation	[113]
12	Anggraeni, S., Nandiyanto, A.B.D., Nurjamil, A.M., (...), Al Husaeni, D.F., Azizah, N.N.	Effect of sawdust, eggshells, rice, husks, and corn husks as fine aggregates on the mechanical properties of concrete	[114]
13	Nandiyanto, A.B.D., Hotimah, A.P., Daffa, M.N., (...), Nadhira, S.F., Anggraeni, S.	The effect of the addition of coconut fibers and coconut shells on the mechanical characteristics of porous concrete	[115]
14	Anggraeni, S., Nandiyanto, A.B.D., Hofifah, S.N., (...), Sopian, O., Saputra, Z.	Effect of biomass comparison of rice straw and eggshell in a porous concrete mixture	[116]
15	Nandiyanto, A.B.D., Al Husaeni, D.N., Ragadhita, R., (...), Al Husaeni, D.F., Aziz, M.	Resin Matrix Composition on the Performance of Brake Pads Made from Durian Seeds: From Computational Bibliometric Literature Analysis to Experiment	[117]
16	Anggraeni, S., Nandiyanto, A.B.D., Pribadi, A.R., (...), Syabina, R.H., Girsang, G.C.S.	The effect of rice husk composition on porous concrete performance	[118]

17	Nandiyanto, A.B.D., Hofifah, S.N., Anggraeni, S., (...), Sopian, O., Saputra, Z.	Physicochemical and mechanical properties of briquettes prepared from the combination of micrometer-sized areca nutshell, tofu dreg, and citronella: from the literature review to experiments	[119]
18	Nandiyanto, A.B.D., Ragadhita, R., Girsang, G.C.S., (...), Valensia, Setiadi, D.P.	Effect of palm fronds and rice husk composition ratio on the mechanical properties of composite-based brake pad	[120]
19	Nandiyanto, A.B.D., Ragadhita, R., Fiandini, M., (...), Al Husaeni, D.N., Fadhillah, F.	Domestic waste (eggshells and banana peels particles) as sustainable and renewable resources for improving resin-based brakepad performance: Bibliometric literature review, techno-economic analysis, dual-sized reinforcing experiments, to comparison with commercial product	[121]

Nanotechnology includes the development and application of very small materials or devices. This material or device is located in the range of 1 to 100 nanometers (nm). One nanometer is equal to one-billionth of a meter (0.000000001 m), which is 50,000 times the size of a human hair. The interval from 1 to 100 nanometers is a measurement that scientists call the nanoscale. Nano-crystals or nano-materials are terms used to describe the materials found in this space.

The use of nanotechnology can be useful and has the potential to have a significant impact on society [122-128]. Currently, nanotechnology has been used by industrial sectors, such as the information and communications sector, food technology, and energy technology, as well as several medical products and medicines. In addition, nanotechnology also offers new opportunities to reduce environmental pollution.

There are many potential benefits of nanotechnology. Nanotechnology can be used to improve materials, nano materials can be stronger, lighter and more durable than traditional materials [129-136]. These improvements can be applied to a wide range of applications across a number of industries including construction, transportation, and consumer products. In addition, nanotechnology can be used to increase energy efficiency, through nanomaterials to make more efficient batteries and solar cells. These materials can help reduce our dependence on fossil fuels and reduce greenhouse gas emissions. In the field of nanotechnology media can be utilized for improved medical care. Nanotechnology can be used to create more targeted and effective drugs, as well as diagnostic tools and medical equipment. Apart from that, nanotechnology can be used to make filters that are more effective in removing contaminants from water. With the help of nanotechnology, it is possible to create sensors to detect food contaminants, as well as fertilizers and pesticides that are more targeted and less harmful to the environment.

3.3 Correlation between CFD and Nanotechnology

Computational Fluid Dynamics (CFD) and nanotechnology have a close relationship in various applications in industry and in the world of researchers. Nanotechnology is a branch of science and engineering aimed at designing, producing and using structures, devices and systems by manipulating atoms and molecules on the nanoscale, that is, having one or more dimensions on the order of 100 nanometers (100 million millimeters) or less [137-144]. CFD itself is a tool that can be used to model and analyze fluid behavior at the nanometer scale which is very important in the development and understanding of nanotechnology. This shows that CFD allows the simulation of fluid flow at the scale required by nanotechnology. CFD helps understand interactions between fluids and nanomaterial or nanoparticle structures [145,146]. As research conducted by Schroeter *et al.,* [147] who performed CFD simulations on a complete nasal passage model of adult male Sprague-Dawley rats to predict regional deposition patterns of inhaled particles in the size range of 1 nm to 10 µm.

CFD can be used to design and optimize nanomaterials with specific properties. For example, in the development of nanoparticles for drug delivery, CFD can be used to simulate the movement of particles and the way they interact in the bloodstream. CFD can help in optimizing particle shape and size for maximum efficiency. Additionally, in nanotechnology applications such as the development of nanofluid-based cooling, CFD helps model heat and mass transfer at the nanoscale. This can help researchers understand and control thermal processes in various nanotechnology applications.

Overall, the relationship between CFD and nanotechnology is very close because CFD provides important tools for understanding, designing, and optimizing various processes and devices at the nanoscale. CFD enables faster and more efficient progress in a variety of nanotechnology applications. Therefore, in this research, we also try to look at the correlation research trend between CFD and Nanotechnology. This was done as an effort to help the development of research and the use of CFD in the field of nanotechnology, as well as to facilitate researchers' considerations when conducting research using CFD in the field of nanotechnology.

Based on the search results, it is known that the year range for research publication articles regarding Computational Fluid Dynamics (CFD) and Nanotechnology used in this research is from 2001 to 2024 with a total of 193 documents sourced from 124 journals and other published institutions. In total, there are 671 authors who have contributed to research on CFD and nanotechnology published in Scopus indexed publications with 10 authors of single-authored documents. Table 6 shows examples of research on CFD and nanotechnology that have been published in Scopus indexed journals with the highest number of citations.

Table 6
CFD and Nanotechnology research articles

Title	Year	Citation	References
Numerical study of convective heat transfer of nanofluids: A review	2016	243	[147]
Liquid slip flow in a network of shale noncircular nanopores	2016	139	[148]
Steps optimization and productivity enhancement in a nanofluid cascade solar still	2018	132	[149]
Pore structure characterization of coal by synchrotron radiation nano-CT	2018	130	[150]
Influence of surface roughness on the initial formation of biofilm	2015	98	[151]
Solar stills: A review of the latest developments in numerical simulations	2016	86	[152]
Experimental and numerical investigation of volumetric versus surface solar absorbers for a concentrated solar thermal collector	2016	63	[153]
Evaluation of Enhanced Condensational Growth (ECG) for controlled respiratory drug delivery in a mouth-throat and upper tracheobronchial model	2010	63	[154]
Numerical modelling of nanoparticle deposition in the nasal cavity and the tracheobronchial airway	2011	56	[155]
The effect of nanoparticles on wettability alteration for enhanced oil recovery: micromodel experimental studies and CFD simulation	2019	54	[156]

3.4 Developments in CFD Research on Nanotechnology per Year

The number of publications regarding Computational Fluid Dynamics (CFD) and Nanotechnology in Scopus has an annual growth rate of 8.1% with details as shown in Figure 1, namely in 2001 there was 1 article, 2002 there were no published articles, 2003 there was 1 article, 2004 there were 4 articles, 22005 2 articles, 2006 3 articles, 2007 5 articles, 2008 10 articles, 2009 7 articles, 2010 12 articles, 2011 7 articles, 2012 13 articles, 2013 11 articles, 2014 10 articles, 2015 as many as 10 articles, 2016 as many as 14 articles, 2017 as many as 7 articles, 2018 as many as 19 articles, 2019 as many as 14 articles, 2020 as many as 15 articles, 2021 as many as 8 articles, 2022 as many as 8 articles, 2023 as many as 7 articles, and 2024 as many as 6 articles.

Based on the data in Figure 1, the development of article publications on CFD and nanotechnology in Scopus has a tendency to increase from the beginning of 2001 to 2024. The increase in CFD and nanotechnology research appears to be stable only in the period 2005 to 2008. In the range of 2018 to 2024 there will be a decline. Meanwhile, from 2009 to 2019, the number of publications regarding CFD and nanotechnology in Scopus fluctuated, meaning that sometimes the number of studies increased in the following year and sometimes decreased in the following year when compared to the previous year. The number of article publications regarding CFD and nanotechnology in Scopus occurred in 2018 with 18 publications and the lowest number of publications occurred in 2002 with 0 publications.

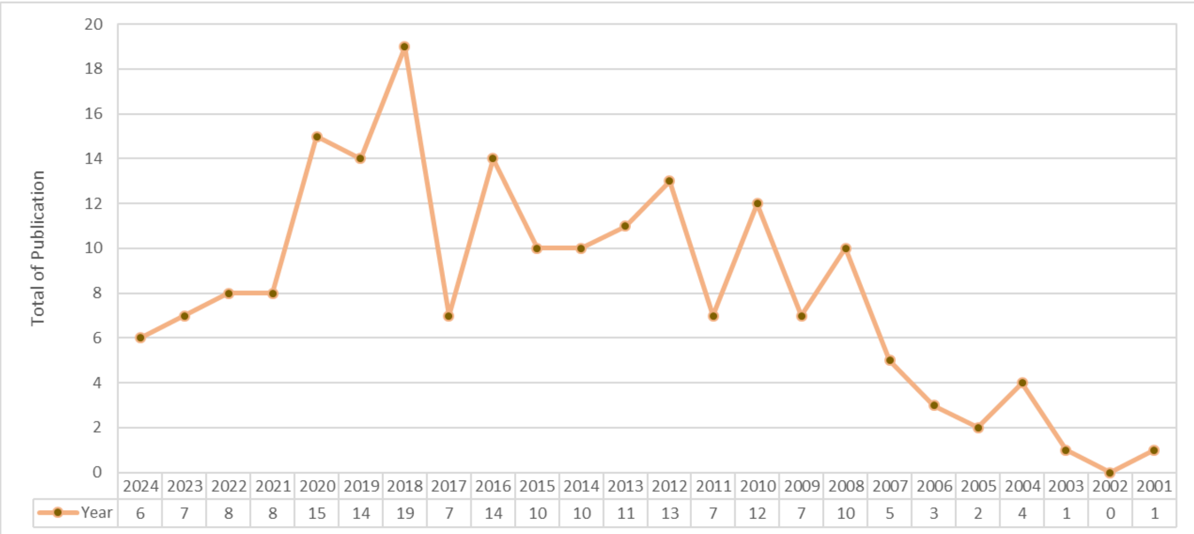

Fig. 1. Annual scientific production

We analyzed other identifications of research developments regarding the correlation between CFD and nanotechnology based on the average citations per year. Publications regarding CFD and nanotechnology in Scopus have an average citation per document of 11.85, while the annual detailed reports are shown in Table 7. Based on citation data, it is known that the highest average number of citations per article occurred in 2016 with an average total of citations per 42.71 articles with a total of 14 articles with an average total citations per year of 4.75. This result is seen more clearly in Figure 2.

Table 7
Average Citations Per Year

Year	MeanTCperArt	N	MeanTCperYear	CitableYears
2001	0	1.00	0.00	24
2003	0	1.00	0.00	22
2004	2.5	4.00	0.12	21
2005	2.5	2.00	0.12	20
2006	1	3.00	0.05	19
2007	8.6	5.00	0.48	18
2008	1.7	10.00	0.10	17
2009	6.71	7.00	0.42	16
2010	9.42	12.00	0.63	15
2011	15.29	7.00	1.09	14
2012	10.62	13.00	0.82	13
2013	2.1	10.00	0.18	12
2014	8.3	10.00	0.75	11

2015	20.8	10.00	2.08	10
2016	42.71	14.00	4.75	9
2017	10.14	7.00	1.27	8
2018	18.63	19.00	2.66	7
2019	14.71	14.00	2.45	6
2020	6.07	15.00	1.21	5
2021	9.88	8.00	2.47	4
2022	9.12	8.00	3.04	3
2023	2.43	7.00	1.22	2
2024	0.5	6.00	0.50	1

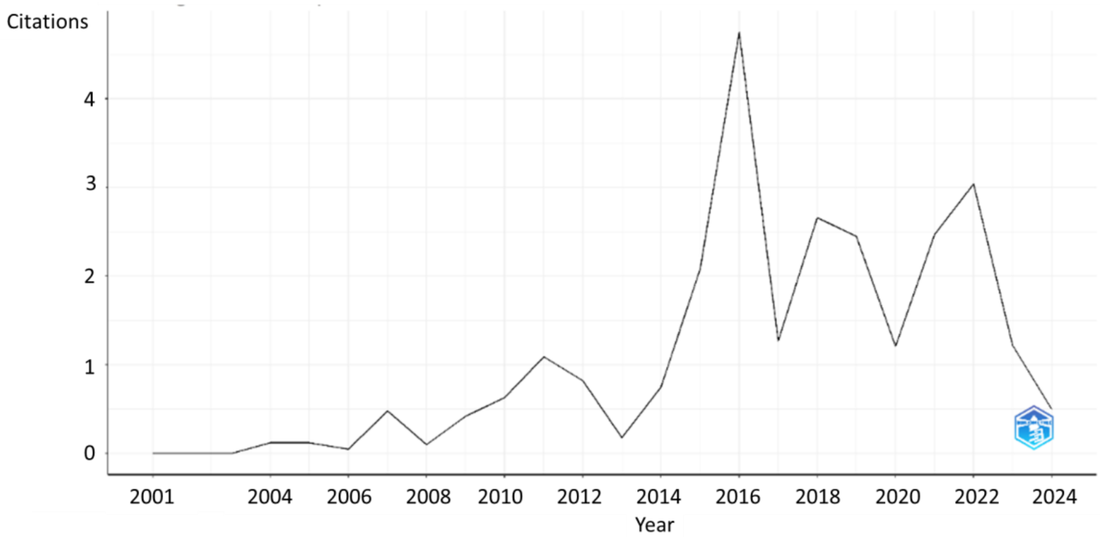

Fig. 2. Average citations per year

The development of research on CFD and nanotechnology can be caused by several factors. One of them is the increasing interest in research regarding CFD and nanotechnology, if we look at the increasingly significant advances in technology and methodology, especially since the fourth industrial revolution which began at the beginning of the 21st century until now or known as the Industrial 4.0 era. In the industrial era 4.0, the integration of digital technology with physical systems, such as the Internet of Things (IoT), artificial intelligence (AI), robotics, biotechnology, nanotechnology, and big data analytics is increasingly being used [157]. These technologies are driving unprecedented automation and connectivity across industries.

Therefore, technological and methodological developments in the Industry 4.0 era are changing the industrial landscape significantly and indirectly changing the direction of research interest towards new ways to optimize production processes, increase efficiency, and develop more sophisticated products and services. This is because when a research program is organized, relevant researchers and industry interests must be identified [158]. In addition, in arranging research support, industry's need for qualified researchers is the main target, while the research program itself is implemented within the academic system [158].

3.5 Trend in CFD and Nanotechnology Research Topics

Figure 3 shows the 10 words that appear most frequently on the topic of CFD and nanotechnology research. Based on Figure 3, it is known that the words Computational Fluid Dynamics appear most often with a total of 173 occurrences and Nanotechnology is in second place with a total of 155 occurrences. Meanwhile, other terms include microfluidics and particle size with 33 occurrences, nanoparticles with 30 occurrences, articles with 27 occurrences, computer simulation with 20 occurrences, computational fluid dynamics simulations with 18 occurrences, precision engineering with 18 occurrences, and hydrodynamics with 17 occurrences.

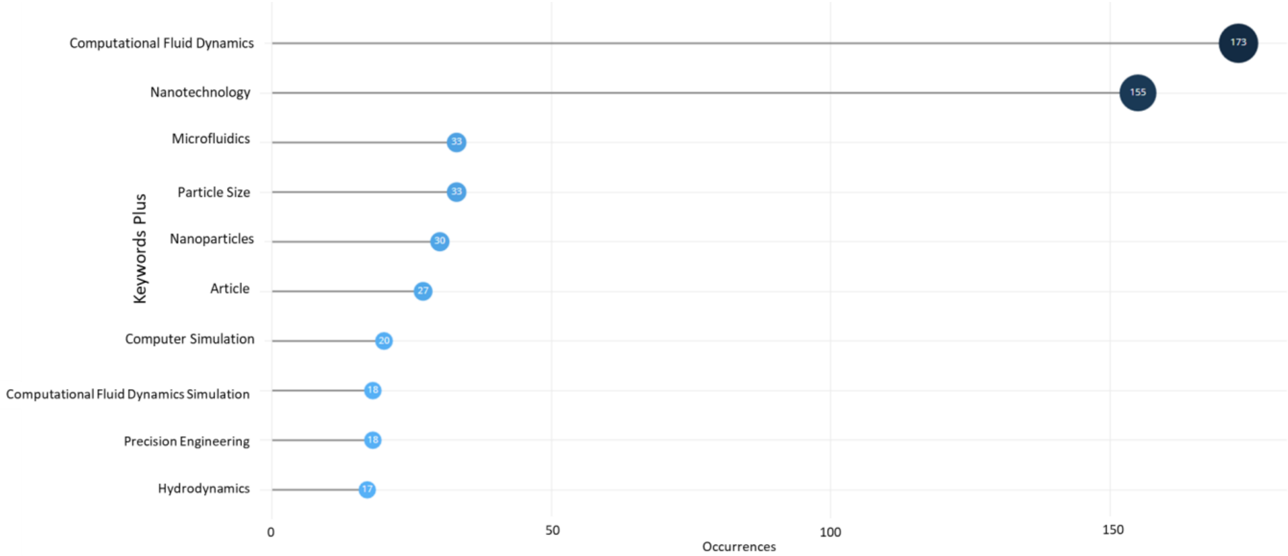

Fig. 3. Most frequent words

Figure 4 shows the trend of research topics generated using RStudio analysis. Figure 4 shows that the larger the circle in the graph, the greater the frequency found in the bibliometric data of CFD and nanotechnology research data used in this research. The analysis in Figure 4 is calculated based on the bottom quartile year (Q1), median year (Q2), and top quartile year (Q3). In this research, the topic of CFD became a research trend in the period 2012 to 2019 with the highest trend in 2016. Meanwhile, the topic of nanotechnology became a research trend from 2010 to 2018 with the highest trend in 2014. Detailed information for the research trends is shown in Figure 4.

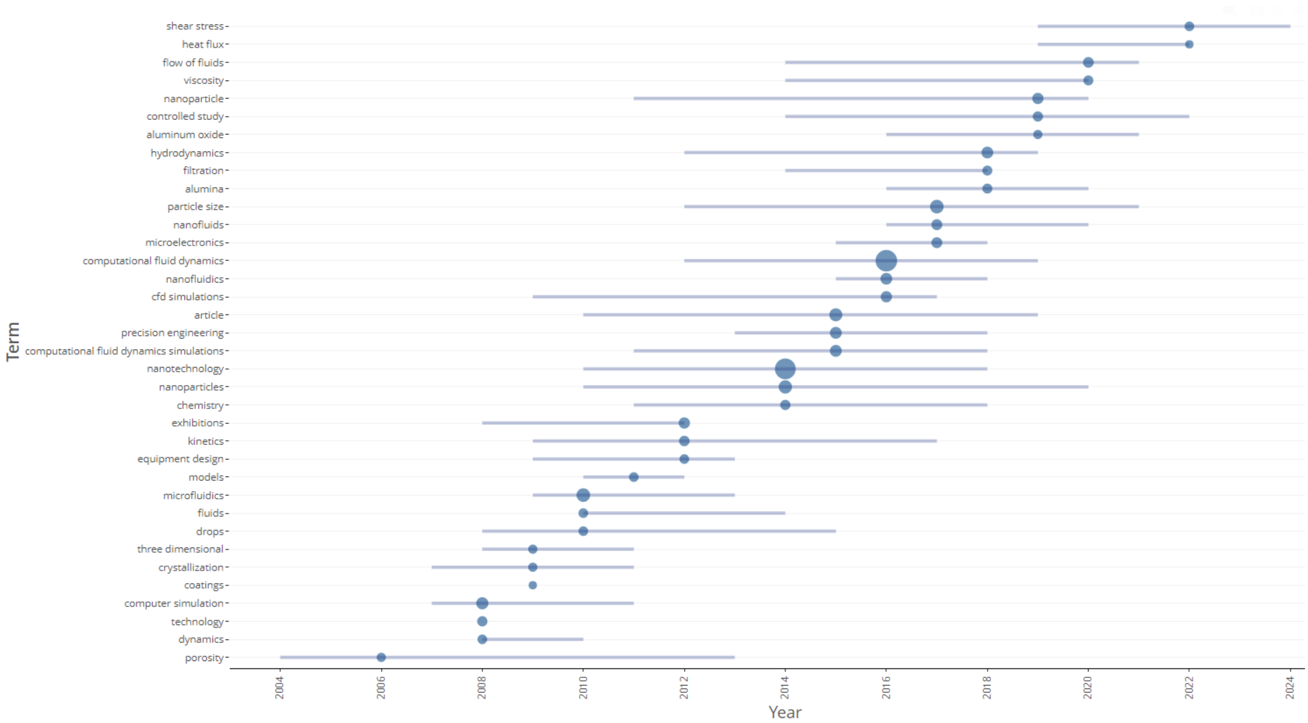

Fig. 4. Trend topics

3.6 Mapping Visualization of CFD and Nanotechnology Research

Visualization mapping is carried out using the VOSviewer application. In this research, there are several provisions during the creation of network visualization type visualization mapping, namely the minimum number of occurrences of a term is 10 and the terms used are 60% of the most relevant terms. Thus, 22 terms were found which were divided into 3 clusters. Figure 5 shows the relationship between terms used in CFD and nanotechnology research. The results of this analysis can be used as a reference for discussion and search for research topics related to the use of CFD in the field of nanotechnology. The different colors of the circles and lines shown in Figure 5 indicate the clusters of each term.

i. Cluster 1 is shown in red and consists of 9 items, namely accuracy, computational fluid dynamics, development, flow field, fluid flow, numerical simulation, particle, particle size, and simulation result.
ii. Cluster 2 is shown in green which consists of 8 items, namely CFD simulation, concentration, investigation, nanofluid, nanoparticle, performance, temperature, and water.
iii. Cluster 3 is shown in blue which consists of 5 items, namely CFD analysis, Comparison, experimental result, good agreement, and numerical model.

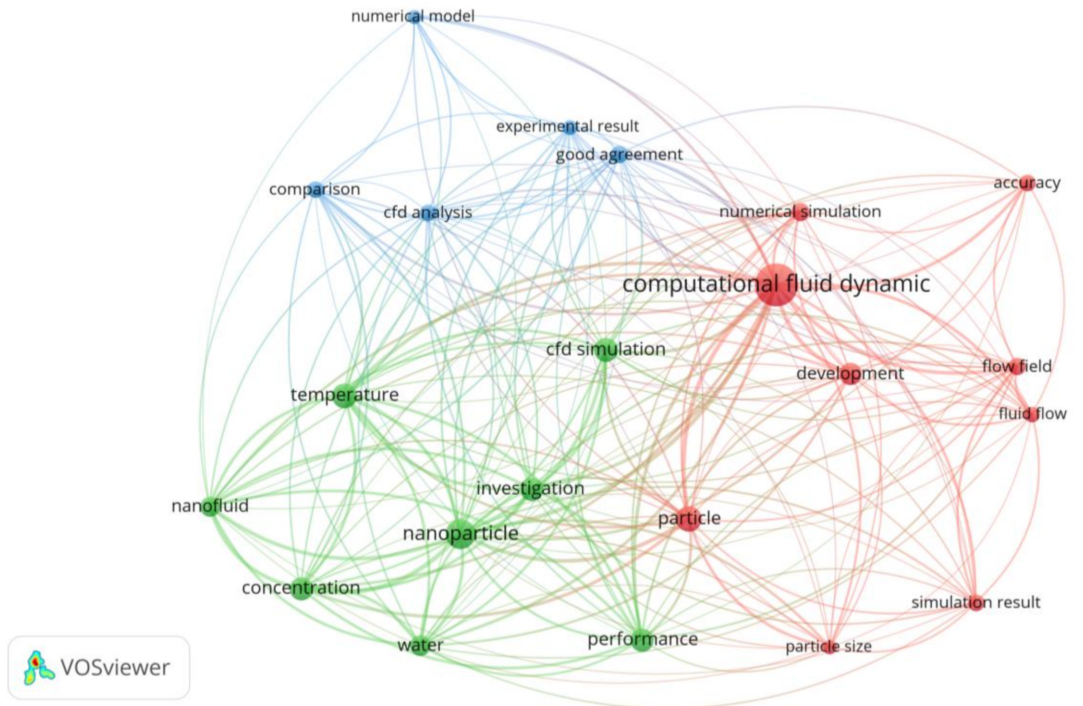

Fig. 5. Network visualization

4. Conclusions

This research aims to find the relationship between CFD and nanotechnology. This research also carries out bibliometric analysis to determine trends in CFD and nanotechnology research. This research shows that the relationship between CFD and nanotechnology is very close because CFD provides important tools for understanding, designing, and optimizing various processes and devices at the nanoscale. CFD enables faster and more efficient progress in a variety of nanotechnology applications. Based on search results from 2001 to 2024 with a total of 193 documents, the development of article publications regarding CFD and nanotechnology in Scopus has a tendency to increase from the beginning of 2001 to 2024. Publications regarding CFD and nanotechnology in Scopus have an average citation per document of 11.85. In this research, it is known that the topic of CFD became a research trend in the period 2012 to 2019 with the highest trend in 2016. Meanwhile, the topic of nanotechnology became a research trend in 2010 to 2018 with the highest trend in 2014. Research developments regarding CFD and nanotechnology can be due to increasingly significant advances in technology and methodology, especially since the Industrial Revolution 4.0.

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