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RESEARCH PAPER

Centralized exchanges vs. decentralized exchanges in cryptocurrency markets: A systematic literature review

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Abstract
Research on cryptocurrency exchanges, consisting of both centralized exchanges (CEXs) and decentralized exchanges (DEXs), has seen a significant increase in contributions in recent years, driven by growing interest in the conceptual design of cryptocurrency markets. Through a comprehensive review of literature published between January 2019 and September 2023, I identify and analyze different dimensions of the ongoing CEX vs. DEX debate. While DEXs emphasize decentralization, user control, and resistance to censorship, CEXs offer higher liquidity, advanced trading features, and a more established track record. Regulatory challenges, such as Know Your Customer (KYC) and Anti-Money Laundering (AML) compliance, also feature prominently in the literature and influence the choice of exchange for both traders and policymakers. In addition, I observe a growing interest in the design of pricing functions for CEXs and DEXs, particularly in the area of automated market makers (AMMs). Finally, based on my findings, I outline future research opportunities in this context and derive research gaps as well as recommended actions for practitioners.

Keywords Automated market maker · Cryptocurrency · Decentralized exchanges · Systematic literature review

JEL Classification G15 · L10

Introduction

In recent years, the cryptocurrency market has undergone a remarkable transformation, evolving from an obscure realm of tech enthusiasts into a global financial ecosystem of significant importance (Bouri et al., 2019). This evolution has been underpinned by technological advancements and innovations, with both centralized exchanges (CEXs) and decentralized exchanges (DEXs) emerging as critical factors in shaping the market's trajectory. With the surpassing of a monthly trading volume of over $4,000B on CEXs and over $200B on DEXs in May 2021, spot trading on CEXs and DEXs reached its peak, increasing more than sevenfold within half a year, as can be seen in Fig. 1. In the subsequent months of the cryptocurrency bull run of 2021, DEXs experienced proportional more growth in their share of trading volume on cryptocurrency markets then their central counterpart, which could be attributed to the launch of UniswapV3, one of the most successful DEX nowadays (Adams et al., 2021; Hashemseresht & Pourpouneh, 2022). Since the beginning of 2022, the volume appears to be declining on both CEXs and DEXs, with DEXs showing a comparatively smaller decrease in trading volume compared to CEXs. One reason for this could be, in part, the unexpected insolvency of the CEX FTX in November 2022, which caused general uncertainty in the cryptocurrency market (Yaffe-Bellany, 2022) and compelled CEXs to improve the transparency in managing their customer funds in order to regain or strengthen their customer's trust (Li, 2023).

The inception of CEXs and DEXs can be traced back to the early days of cryptocurrency trading. Centralized exchanges, like the infamous Mt. Gox (Greenberg, 2014; Mohan, 2022), established the initial framework for trading cryptocurrencies against traditional fiat currencies. While these platforms played a crucial role in the market's inception, they displayed vulnerabilities to security breaches, regulatory oversight,

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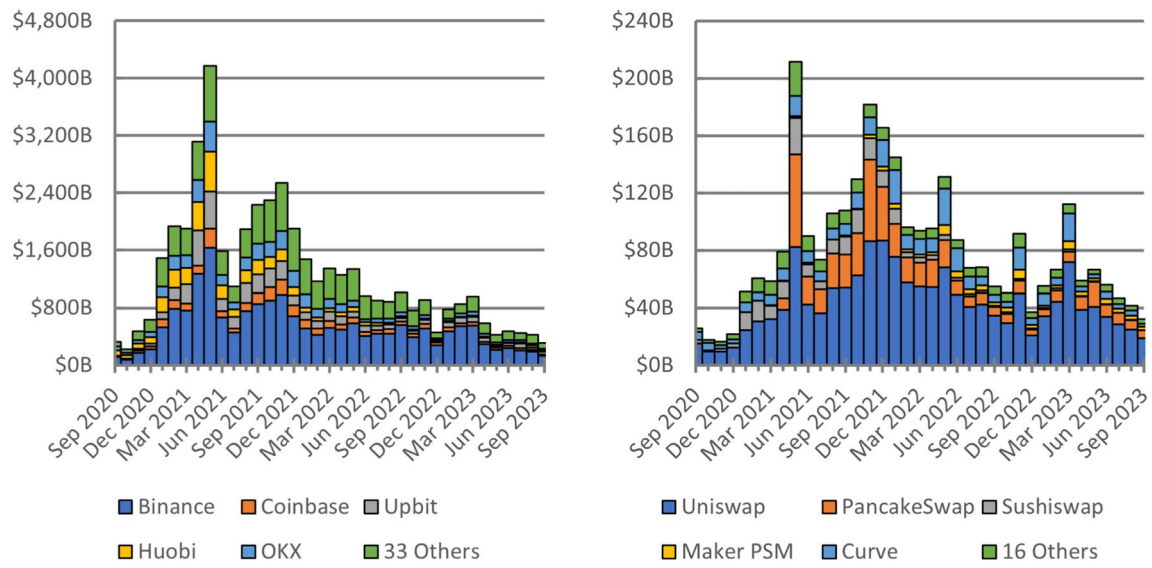

Fig. 1 Spot trading volume on CEXs (left) and DEXs (right) from September 2020 to September 2023 based on data obtained from The Block (2023a) and The Block (2023b)

and operational limitations (Caliskan, 2020; Chohan, 2022). Concurrently, the concept of DEX emerged as a response to the inherent limitations of CEX (Lo & Medda, 2020). The core principle behind DEX was to create trusted, peer-to-peer platforms that give users control over their private keys and assets (Dai, 2020). However, it was not until the advent of Ethereum's smart contract functionality that DEX began to demonstrate substantial viability. Uniswap, an Ethereum-based DEX, emerged as one of the most successful projects into this domain (Adams, 2018; Koroļkovs & Kodors, 2022), diverging from and evolving the automated market-making (AMM) model previously implemented by the Bancor protocol (Hertzog et al., 2017; Ottina et al., 2023). Uniswap with its V2 later became the first DEX to surpass a daily trading volume of over $1B on October 26, 2020 (Adams, 2018; DefiLlama, 2023), and conducted one of the most successful token airdrops to date (Makridis et al., 2023).

Meanwhile, the cryptocurrency exchange ecosystem in the cryptocurrency markets has expanded considerably. Notably, DEXs have surpassed their centralized counterparts in numbers, with ~ 500 DEXs compared to ~ 300 CEXs as of October 2023 (CoinGecko, 2023). This trend can mainly be attributed to the relative ease with which DEXs can be distributed and established. For example, the once leading DEX, SushiSwap, started as an emulation of its competitor, Uniswap (Wang, 2022). Nevertheless, what sometimes began with mere imitations has — like CEXs — since transformed into a diverse range of distinct protocols, encompassing various economic relationships such as cryptocurrency trading, cryptocurrency barter, or even cryptocurrency banking. As a result, categorizing and differentiating the complexities represented by these protocols with the definitions provided by the existing academic literature often proves challenging due to the evolving nature of the cryptocurrency exchange industry. For instance, Xia et al. (2020, p. 2) define CEXs as exchanges, which are "governed by a company or an organization" while DEXs "provide *automated process* [emphasis added] for peer-to-peer trades." However, there are a lot of DEXs using their governance tokens like UNI, SNX, or BAL to make decisions regarding the protocol and thereby act as a decentralized autonomous organization (DAO) (Wang et al., 2023) that could be categorized as CEXs with this definition. Additionally, there are also some CEXs like Binance (2023) that offer P2P trades to their customers, which could be automatized using API bots and therefore may apply as DEXs depending on the interpretation of automated processing in the aforementioned definition. Some of the academic works also list hybrid (cryptocurrency) exchanges (HEX) as an alternative to the strict differentiation between CEXs and DEXs (e.g., Luo et al., 2019; Qin et al., 2021). However, they specify either not at all or only very imprecisely what characteristics a cryptocurrency exchange must have to be classified as a HEX. For instance, Luo et al., (2019, p. 48) only give the information that "a HEX maintains a centralized database to provide matching services for the traders, while all transactions are still executed by smart contracts hosted in a blockchain." With a definition like this, it raises the question, especially, to what extent centralization of a database suffices as a criterion to no longer be considered a DEX, particularly since many DEXs also provide a certain form of a central database through their user interfaces in the form of a website, and sometimes, matching services as well (Brasse & Hyun, 2023). For example, the exchange 1inch offers traders the possibility to set limit orders using

their web interface, which gets managed and operated by the 1inch Foundation (1inch, 2023), a NPO and DAO. In accordance with the previous definition, it would be necessary to determine to what extent a DAO or NPO should indeed be classified as a criterion for a HEX. In academic literature, however, 1inch is classified as a DEX despite the presence of a central database (Boonpeam et al., 2021; Cola et al., 2023; Kitzler et al., 2023; Xu et al., 2023). The blurred distinction between CEXs and DEXs, especially HEXs, reflects the diversity of exchange concepts in the cryptocurrency market and academic literature. This calls for a systematic elaboration of the characteristics and dimensions of cryptocurrency exchanges and the development of a classification framework.

For this reason, I conduct a secondary study in the form of a review of the literature on cryptocurrency exchanges, acknowledging the complexities of both CEXs and DEXs, but focusing primarily on the marketized processes within them as their most prominent use case. Here, a systematic review approach is particularly advisable due to the diversity of published literature on the topic of CEXs and DEXs. In addition, it allows for a consolidation of the current state of research and facilitates the drawing of conclusions from a condensed pool of information, which is valuable due to the comprehensive insights it provides. First, I identify and analyze existing papers on CEXs and DEXs using a systematic method, focusing on their mentioned characteristics as well as the dimensions explored by the academic literature. This enables a downstream analysis of popular topics and helps to identify promising research gaps. A systematic literature review combines results from different methodical approaches into a unified contribution, thereby reducing the impact of subjectivity associated with individual articles. To the best of my knowledge, there are only two (systematic) reviews in the literature that focus on CEXs and DEXs. Eigelshoven et al. (2021) use a systematic approach to investigate the vulnerability of the CEX and DEX to market manipulation. In their conference paper, they identify seven manipulation methods and six indicators of the success of market manipulation schemes. However, a detailed differentiation between CEXs and DEXs and their characteristics is missing. The final sample size of 38 is also rather limited. On the other hand, Y. Chen et al., (2023b) focus their research report on the cryptocurrency trading infrastructure, differentiating between CEXs and DEXs. However, their work is primarily focused on collecting survey results rather than systematically capturing current research in the cryptocurrency exchange space. Consequently, it does not reach the depth of a systematic literature review. Thus, there is a need for a new, in-depth investigation to systematize the exchange landscape in the cryptocurrency market.

The remainder of this paper is organized as follows. The "Methodology" section provides an overview of the proposed methodology, followed by a description of the design of the conceptual framework. This framework uses several superordinate terms to assess the current state of research on CEXs and DEXs. The "Descriptive analysis of the literature sample" section presents and analyzes the descriptive characteristics of the literature in the literature sample. The "Discussion of the secondary study results" section discusses the findings in the context of the established framework, delving into the characteristics, advantages, and disadvantages of different cryptocurrency exchanges and formally defining CEXs and DEXs. The "Open research questions and future directions" section highlights the potential research directions that have emerged from the analysis of the literature sample. Finally, the "Conclusion" section summarizes the conclusions of the study and discusses the implications and limitations of the research.

Methodology

Literature search and selection strategy

Secondary studies, such as literature reviews, require a comprehensive and reliable sample of literature to ensure that readers can thoroughly evaluate and understand research findings (Sauer & Seuring, 2023). The primary goal of a literature review is to organize the existing literature on a topic in order to examine the current state of research and identify any existing research gaps (Grisar & Meyer, 2016). Literature reviews are conventionally categorized into four distinct types: narrative reviews, scoping reviews, systematic reviews, and meta-analyses, each distinguished by their approach for assembling a literature sample (Hochrein & Glock, 2012). Narrative reviews do not explain the development of their literature sample and often fail to methodically document the literature search process, making it difficult or even impossible for readers to replicate the findings, especially when the research results depend on the selection of reviewed articles within a particular research area (Massaro et al., 2016). In contrast to narrative reviews, scoping reviews aim to identify and describe the available evidence on a particular topic, with a particular focus on clarifying key concepts and definitions found in the relevant literature. They delve into the methods used to research a particular topic or field, and seek to uncover and analyze any prevailing gaps in knowledge (Munn et al., 2018). Due to their exploratory nature, scoping reviews often serve as a precursor to systematic literature reviews, which use a systematic method to generate a literature sample (Paul et al., 2021). The fundamental aim of a systematic literature review is to provide a structured, comprehensive, and truthful overview of the

current state of the art. Consequently, systematic reviews are considered to be the most unbiased form of literature review. It is not uncommon for data from systematic reviews to be extracted and subsequently used as the basic framework for conducting a meta-analysis (Hägele et al., 2023). Finally, meta-analyses primarily use statistical techniques to evaluate an existing sample of literature, making them primarily quantitative in nature (Snyder, 2019). My method is designed to systematically identify the research dimensions of CEX and DEX research in cryptocurrency markets. To achieve this, I conduct a systematic literature search following the methods outlined by Denyer and Tranfield (2009), Stone and Rahimifard (2018), and Hägele et al. (2023) to identify relevant literature review articles. As shown in Fig. 2, the approach follows five sequential steps that are condensed into the systematic research method used to specify the literature sample.

1. *Developing research questions:* the first step focuses on formulating research questions that will guide the systematic literature review. This is done with a particular emphasis on the research objective, which is to determine the dimensions of research related to CEXs and DEXs. Therefore, the following questions are specified:

   RQ1: What is the current understanding of CEXs and DEXs in the literature? Is there a common definition or does the understanding vary widely?

   RQ2: What CEX and DEX dimensions are addressed in the literature? Is it possible to identify a particular research focus or trending topics in the cryptocurrency exchange literature? Are some dimensions less or not focused on, thus creating research gaps?

   RQ3: What are the pricing features currently used in CEXs and DEXs? Are they similar, or are there variations that only exist on one of the two cryptocurrency exchanges?

2. *Database search and retrieval:* the next step is to systematically search the current academic literature for relevant papers. This is done by brainstorming and defining appropriate keywords that are directly related to the research topic, without claiming to be exhaustive. Variations of the keywords are then added to the pool to account for differences in spelling. Finally, the keywords are divided into two groups and linked within each group using the logical operator OR, while both groups are linked together using the logical operator AND. The resulting search string is then used in scientific databases such as Ebsco Host, Elsevier, Emerald, Google Scholar, Springer Link, Web of Science, and Wiley Online. The search is conducted in October 2023 and includes all publications up to September 2023. The groups defined and the keywords used are shown in Table 1.
3. *Screening and selection:* in this step, the literature is systematically reviewed for alignment with the research objectives using the PRISMA approach (e.g., Rethlefsen

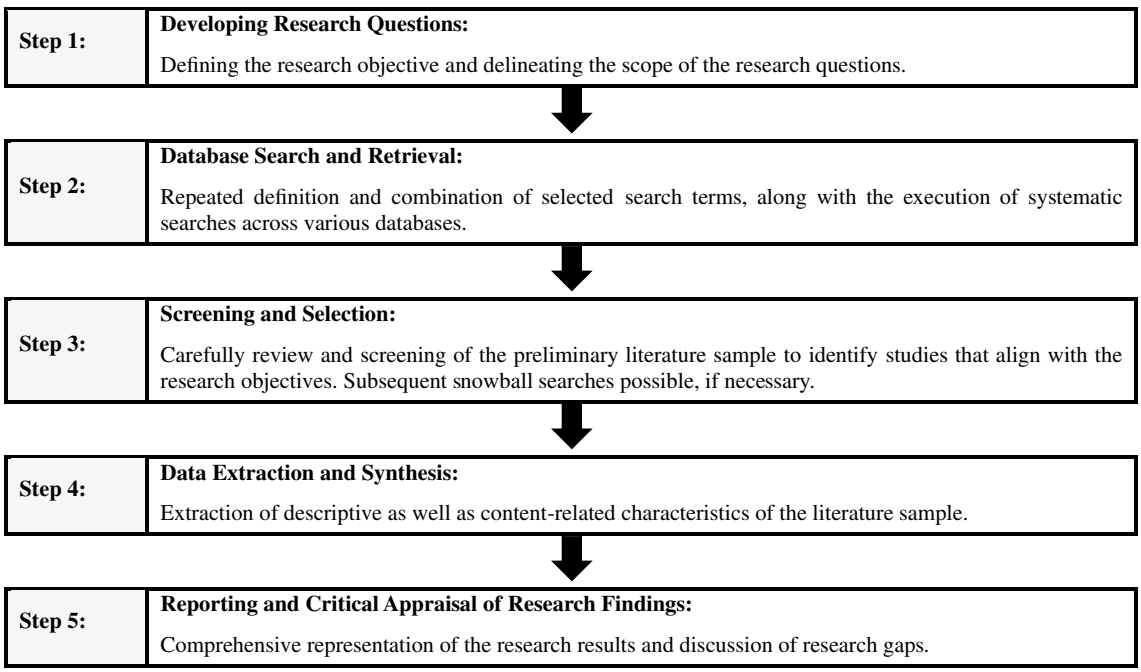

Fig. 2 Literature search and review method adapted from Denyer and Tranfield, (2009), Stone and Rahimifard (2018), and Hägele et al. (2023)

Table 1 Keywords used in the database search

Group A: search strings related to CEXs or DEXs	Group B: search strings related to cryptocurrency markets
"AMM"	"Bitcoin"
"Automated Market Maker/ing"	"Blockchain/s"
"Bitcoin Exchange/s"	"Coin/s"
"CEX/s"	"Cryptocurrency/ies"
"Centralized"	"Cryptocurrency Market/s"
"Centralized Exchange/s"	"DeFi"
"Cryptocurrency Exchange/s"	"Decentralized Finance"
"DEX/s"	"Market/s"
"Decentralized"	"Market Quality"
"Decentralized Exchange/s"	"Marketplace/s"
"Exchange/s"	"Token/s"
"Liquid/ity"	"Trade/s"
"Order"	"Transaction/s"
"Order Book/s"	
"Trade/ing"	
"Volume"	

et al., 2021), as shown in Fig. 3. For each paper suggested by the database search, the first step is to check whether it is already part of the literature sample. If not, the abstract of the paper is reviewed to assess its suitability for addressing one or more of the research questions. If suitability cannot be determined from the abstract, the full paper is read and a decision is made whether or not to include it in the sample. After reviewing the database results, the literature cited in the sample papers is also reviewed for eligibility, thus initiating a snowball research process. After reading the initially identified 143 articles, 89 articles remained as the size of the literature sample. Some articles were excluded because they focused more on decentralized finance (DeFi) rather than on DEXs or CEXs (e.g., Schueffel, 2021), or because they appeared to lack sufficient scientific rigor.

4. *Data extraction and synthesis:* after selecting the articles, a critical review is conducted to capture the essential characteristics, central messages, and concepts of the literature sample. Essential information for answering the research questions is captured, while a framework is developed to facilitate categorization and structuring. This framework is iteratively adapted, revised, and developed during the paper review process, ultimately allowing for a systematic representation of the dimensions of CEX and DEX research, as well as the identification of interrelationships, interactions, and research gaps. In addition to content-specific aspects, descriptive characteristics of the papers are also captured to provide a systematic literature review; to gain insight into the origin, distribution, and development of research on the topic; and to provide a foundation for future research building on this work.
5. *Reporting and critical appraisal of research findings:* in the final step, the collected findings are integrated into the framework and condensed for clarity. Information

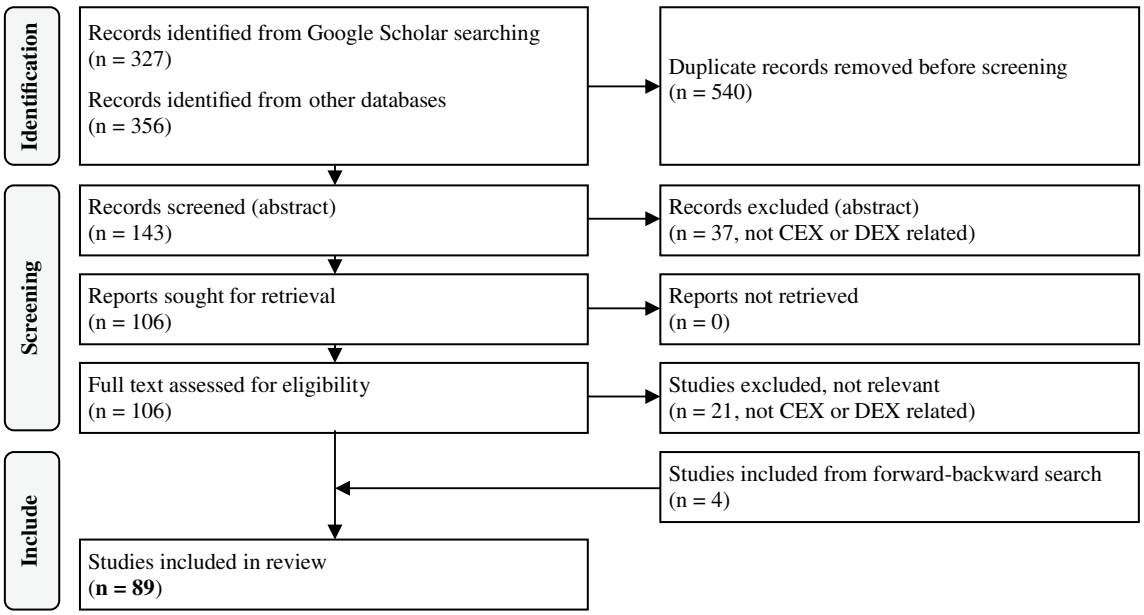

Fig. 3 Process of literature selection based on the PRISMA approach following Denyer and Tranfield (2009), Stone and Rahimifard (2018), and Hägele et al. (2023)

is cross-referenced across research questions to identify superordinate relationships. Finally, the findings are visually presented in an aesthetically pleasing manner for a compact yet informative presentation. A summary of all information collected is also included in Appendices A and B.

Framework development

The goal of the framework development is to systematically capture the dimensions of CEX and DEX research. To achieve this, the first step was to identify and formulate appropriate superordinate terms to facilitate a structured comparison of the characteristics of CEXs and DEXs. The starting point for this objective is to first establish a basic understanding of CEXs and DEXs in cryptocurrency markets. For this reason, all definitions of CEXs and DEXs mentioned in the literature sample are first recorded. Often, these are not explicitly labeled as definitions, which require a clear distinction between characteristics and definitions. In addition, the papers often lack precise or only vague definitions of DEXs and especially CEXs. Therefore, for better comparison, only those papers with definitions that explicitly cover both CEX and DEX are presented in Table 2. However, all identified definitions of CEXs and DEXs can also be found in Appendix B.

When identifying definitions, only language that explicitly named or referred to CEXs or DEXs was considered a definition. Definitions that were not specific to the exchange models, such as "a cryptocurrency exchange is a marketplace where users can buy and sell cryptocurrencies" (Xia et al., 2020, p. 2), were also not included because the focus of this paper is on addressing the research questions and differentiating between CEXs and DEXs. Interestingly, the papers in the literature sample often define specific implementations of DEXs, such as AMMs, without first explaining what a DEX is. When DEXs are defined, it is often in the context of distinguishing them from CEXs, without explicitly outlining what defines a CEX (e.g., Berg et al., 2022; Falakshahi et al., 2021; Fritsch, 2021; Jeong et al., 2023). Furthermore, there are cases where terms such as DeFi and DEXs, although conceptually related, are still used interchangeably (Aigner & Dhaliwal, 2021; Shah et al., 2023). Overall, CEXs are defined much less frequently than DEXs. Only 27 out of 89 papers, or about 30% of all papers in the literature sample, provide a definition for CEXs. Conversely, at least 39 out of 89 papers, or more than 44%, define DEXs. Reasons for this could be the publication date of the papers in the literature sample and the relative novelty of DEXs compared to CEXs. Therefore, the focus is often on the former, while the understanding of the latter, which has been around longer, is assumed to be known.

In addition to collecting and consolidating definitions of CEXs and DEXs, an analysis of the keywords used in the papers from the literature sample is also conducted as part of the framework development. The aim is to gain insight into the methodical focus of the papers and, more importantly, to gather information about their thematic focus in order to identify possible research directions. A total of 306 keywords were extracted from the papers in the literature sample, although not all papers used keywords. The average number of keywords per paper is therefore approximately 3.4, reflecting considerable diversity in keyword selection. After removing keywords that were used in multiple papers, 162 unique keywords remained, which were then further condensed into appropriate categories (see Table 3).

Looking at the absolute frequency of keywords within each category (including repetitions across papers), certain research directions can already be deduced. The focus of the papers from the literature sample seems to revolve around some less surprising category emphases, such as cryptocurrencies, financial markets, or finance in general. However, there is also a notable concentration of papers using keywords related to market infrastructures such as DeFi protocols (e.g., Shah et al., 2023) or networks (Kitzler et al., 2023), especially in the context of market design and, more specifically, pricing functions (e.g., Aoyagi, 2020; Koroļkovs & Kodors, 2022).

After studying the definitions of CEXs and DEXs in the papers from the literature review, I was able to determine both the current understanding of these terms in the academic literature and identify initial trends and emphases through the collection and consolidation of keywords. The next step is to develop a structured and comprehensible framework based on these findings. In the context of the contribution, especially to answer research question 2, superordinate terms are derived for the framework that allow different perspectives on the study of CEXs and DEXs and reflect the frequency of different keyword uses (excluding methodical keywords). As keywords, particularly from the financial domain, were mentioned more frequently, they were subdivided into several superordinate terms: *Market Efficiency*, *Liquidity Provision*, and *User Experience*. From the category of cryptocurrencies and blockchain (see Table 3), the superordinate term *Technological* was chosen to allow for a broader and multifaceted categorization. The aspects of security and ethics from the keyword categorization are adopted with minimal changes as *Security and Trust*, since "trust" and trust-related terms seem to be mentioned more frequently in the literature sample. Finally, a certain regulatory context can be derived from the definitions of CEXs and DEXs. Therefore, the last superordinate term introduced is *Regulatory* to cover all kinds of legal aspects. Figure 4 provides a summary of the derived superordinate terms for the dimensions of CEX and DEX research.

Table 2 Articles of the literature sample with definitions of both CEXs and DEXs

Authors	Definition of CEXs	Definition of DEXs
Aigner and Dhaliwal (2021)	"Centralized exchanges (CEX) (…) are companies in the conventional sense that provide a platform or app to deposit fiat currencies into or offer the option to purchase using credit cards." (p. 8)	"Decentralized exchanges (DEX) (…) have no central entity managing the deposits." (p. 8)
Aspris et al. (2021)	"CEXs in cryptocurrency markets maintain infrastructure similar to that observed in traditional equities markets, with comparable protocols and equivalent trade execution rules fostering the provision of liquidity and the price discovery process." (p. 2)	"DEXs facilitate the exchange of tokens without the need for an intermediary exchange to act as a custodian for their cryptocurrencies." (p. 2) "Their role in the cryptocurrency market in part serves as a vehicle for on-ramping to regulated centralized exchanges where sufficient credibility has been established." (p. 19)
Brasse and Hyun (2023)	"Centralized exchanges (CEXs) are trading platforms that function as an intermediary between traders to buy or sell cryptocurrencies, whether between each other or fiat currencies such as the US dollar." (p. 342)	"Decentralized exchanges (DEXs) facilitate the exchange of cryptoassets by matching and executing trades through smart contracts, allowing traders to reach each other, and set an agreed-upon price." (p. 342)
Y. Chen et al. (2023b)	"The centralized platforms (CEXs), which are owned and operated by a central entity (or consortium of entities) intermediating access to the blockchain (or distributed ledger) where the crypto-assets exist." (p. 9)	"The decentralized, permissionless platforms (DEXs), where there is no central entity operating the platform, participants directly control their assets in the blockchain, and trading and execution happens in the blockchain (…), usually using the AMM protocols." (p. 9)
Eigelshoven et al. (2021)	"Centralized exchanges (CEX) keep the assets of a user in the collective wallet of the exchange and are generally owned by a central organization – such as Coinbase or Binance." (p. 3)	"A decentralized exchange (DEX) use smart contracts or other forms of peer-to-peer networks to execute exchange functionality and enable non-custodial cryptocurrency trading." (p. 3)
Jeong et al. (2023)	"Centralized exchange (CEX) (…) adopts the traditional limit order book (LOB) mechanism that provides cryptocurrency trading with a centralized matching engine." (p. 1)	"Decentralized exchange (DEX) (…) provides direct cryptocurrency tradings through the pools of crypto assets instead of the centralized matching engine in CEX." (p. 1)
Johnson (2020)	"Having abandoned aspects of the public, permissionless blockchain envisioned by early theorists and developers, centralized exchanges relinquished the benefits of transparent, permissionless trading." (p. 1954)	"Unlike a centralized exchange, a DEX is not a single point of failure and is, therefore, far less susceptible to the various security and risk management concerns that plague centralized exchanges." (p. 1957f.)
Luo et al. (2019)	"In a typical CEX, users need to transfer their tokens to a CEX-provided address, which can be accessed through a user-defined ID and password." (p. 48)	"Different from CEX's centralized management on trading operations, DEX implements all trading procedure as smart contracts." (p. 48)
Makridis et al. (2023)	"Centralized exchanges require users to deposit currencies into 'hot wallets', which are centralized repositories. The centralized exchange maintains private cryptographic keys, which unlock these wallets." (p. 1)	"DEXs are non-custodial: cryptocurrency remains in each user's wallet. DEXs perform transactions through smart contracts, or computer programs that automatically execute when certain conditions are met." (p. 1)
Matkovskyy (2019)	"Centralized bitcoin exchanges include intermediaries such as companies that act as a proxy in order to facilitate trading." (p. 270)	"Unlike centralized exchanges, the decentralized market is a person-to-person (P2P) bitcoin trading site that allows users to post advertisements indicating exchange rates and payment methods for buying or selling bitcoins without disclosing their identities." (p. 270)
Milionis et al. (2023a)	"In centralized exchanges such as Coinbase or Binance, users hand control of their assets over to the exchange and must accept the credit risk of not getting them back." (p. 2)	"Decentralized exchanges (DEXs), meanwhile, operate purely programmatically (i.e., 'on-chain'), are typically non-custodial (meaning that traders at all times have direct control of their assets in the sense that assets are not entrusted to a third party), and often depart from the CLOB model." (p. 2)
Palit (2022)	"Centralized cryptocurrency exchanges such as Coinbase and Binance also use this mechanism where liquidity is provided by limit orders and consumed by market orders." (p. 2)	"DEXs (decentralized exchanges) (…) allow users to supply and source liquidity by interacting through protocols coded as an algorithm that provides an automated market making function." (p. 1)

Table 2 (continued)

Authors	Definition of CEXs	Definition of DEXs
Shah et al. (2023)	"CeFi exchanges require users to transfer their crypto assets' private keys to a third party to conduct payments and coin orders, creating intermediaries in the transaction process." (p. 171)	"Decentralized exchanges are blockchain-based applications that facilitate direct trading of crypto assets among users without relying on intermediaries." (p. 174)
Sylvester et al. (2022)	"Centralized exchanges (CEXs) represent more traditional book-keeping in the form of limit order books." (p. 3)	"AMMs are DEXs that allow buyers and sellers to immediately trade cryptocurrencies with an institution that keeps a reserve of different coins." (p. 3)
Victor and Weintraud (2021)	"A centralized exchange (CEX), sometimes also called a custodial exchange, keeps a user's assets in their collective exchange wallets." (p. 24)	"A decentralized exchange (DEX) is typically implemented as a smart contract, which can allow for the non-custodial trading of cryptoassets." (p. 24)
Xia et al. (2020)	"Centralized exchanges (CEX) (…) is governed by a company or an organization." (p. 2)	"Decentralized exchanges (DEX) (…) provide automated process for peer-to-peer trades." (p. 2)
Xia et al. (2021)	"CEX, as the traditional trading mechanism, requires a central entity as the intermediary to complete cryptocurrency trading between its users. Therefore, the trustworthiness of the middlemen plays a vital role in this trading mechanism, as all the user activities and digital assets are under the control of the central operators." (p. 2)	"To facilitate free trading and eliminate the potential security and privacy issues, DEX is introduced to allow users to trade their cryptocurrencies without transferring the custody of their cryptocurrencies to the middlemen, thereby mitigating the security issues of CEX and providing better privacy by eliminating KYC verification." (p. 2)

Once the superordinate terms have been formulated, the systematic and thorough research of the dimensions of CEX and DEX can begin. To accomplish this, the literature sample is searched for statements related to the specified superordinate terms, and these statements are assigned accordingly. In the comprehensive summary of all statements on the dimensions (see Appendix C), whenever the context allows, a corresponding statement is captured as faithfully as possible. When a verbatim categorization would not make sense due to lack of context, the statement is paraphrased and then recorded. Sometimes statements could theoretically be assigned to multiple categories, for example, "Users can access that liquidity and exchange tokens based on a pricing function dictated by their relative availability in the pool" (Palit, 2022, p. 2). In such cases, these statements are assigned to the category with which they most closely align, even if they could also be assigned to another category. This compromise is made to avoid duplication, although it introduces a degree of subjectivity. After all papers in the literature sample have been critically analyzed, the framework is well populated and it is possible to proceed with the cross-category and cross-exchange analysis. All steps of the framework design, from the systematization of definitions and keywords to the derivation of the superordinate terms of the framework and the description of the assignment of statements, are summarized once again in Fig. 5.

Descriptive analysis of the literature sample

The literature sample consists of 89 review articles on CEXs and DEXs, all of which were published in the years 2019–2023 (or have yet to be published in the case of preprints). At first glance, this narrow publication window may seem unexpected, especially given that no specific restrictions on publication years were imposed during the database search. While the whitepaper for Bitcoin, the first cryptocurrency, was published by Satoshi Nakamoto in 2008 (Nakamoto, 2008), and the foundation for today's DEXs was laid with the Ethereum whitepaper in 2013 (Buterin, 2013), the initial breakthrough of CEXs, and in particular DEXs, remained elusive to the general public until the launch of Uniswap V2 in 2020 (Adams et al., 2020). Consequently, the narrowed publication timeframe of the papers in the literature sample can also be attributed to a surge of scholarly interest in shaping and understanding these novel marketplaces. During this specific publication period, a rapid increase in the number of publications per year can be observed, as shown in Fig. 6, which summarizes all the descriptive characteristics of the literature sample. In addition to the rapid increase in annual publications on CEXs and DEXs, a diversity in the countries of origin of the authors of the papers in the literature sample

Table 3 Keyword categorization and usage in the literature sample

Category	Keyword frequency	Keywords
Cryptocurrencies and blockchain	76	Altcoins, Bitcoin, Blockchain, Centralization, Centralized Cryptocurrencies, Crypto Tokens, Cryptoassets, Cryptocurrencies, Cryptocurrency, Crypto-currency, Cryptocurrency Exchange, Cryptocurrency Exchange Disclosure, Cryptoeconomic Systems, Cryptoeconomy, Cryptofinance, Decentralization, Decentralized Cryptocurrencies, ERC-20, Ethereum, Stablecoins, Terra-Luna, Token Economy, Tokenomics, Tokens
Financial markets and trading	58	Algorithmic Trading, Arbitrage, Asset Management, Automated Agent, Binance, Concentrated Liquidity, Cyclic Arbitrage, Derivatives, Divergence (or Impermanent) and Slippage Losses, Financial Markets, Financial Services, FTX, High-frequency Trading, ICO, Impermanent Gain, Impermanent Loss, Limit Order Book, Limit Order Books, Liquidity, Liquidity Provider, Liquidity Provider and Taker, Liquidity Provision, LP, Margin Liquidity, Market Maker, Market Making, Market Manipulation, Market Microstructure, Market Quality, Optimal Trading, PFL, Portfolio Diversification, Portfolio Management, Portfolio Optimization, Predictable Loss, Profitability, Remain Active, Strategic Liquidity Provision, Trading, Transaction, Uniswap, Volatility, Yield Farming
Technology and methods	31	Agent-based Simulation, ARMA-GARCH Copula, Classification, Composability, Data Mining, Deep Learning, Deep Reinforcement Learning, Domain Typosquatting, Dynamic Programming, Forecasting, Interactive Theorem Proving, Machine Learning, Measurement, Mechanism Design, Predictive Automated Market Making Architecture, Smart Contract, Smart Contract Verification, Smart Contracts, Stochastic Control, Stochastic Optimal Control, Systematic Literature Review, Taxonomy, Zero-intelligence
Finance and economics	54	Asymmetric Information, Auction, Cross-Listing, Crypto Finance, Decentralised Finance, Decentralized Finance, Decentralized Finance (DeFi), DeFi, FinTech, Frequent Batch Auction, Information Efficiency, Interest Rate, Investment Models, Lending and Borrowing, Market, Market Design, Market Efficiency, Money, Price Discovery, Risk, Signals, Welfare Loss
Security and ethics	20	Compliance, Crime, Fairness, Fake App, Fake Volume, Fraud Detection, Front-running, General Order Manipulations, Miner Extractable Value, Money Laundering, Regulation, Regulations, Scam, Scam Cryptocurrency, Security, Self-trades, Trust-trading, Wash Trading
Market infrastructure	67	AMM, Automated Liquidity Providers, Automated Market Maker, Automated Market Maker (AMM), Automated Market Makers, Automated Market Making, Automatic Market Maker, Automatic Market Makers, Centralized Exchange, Centralized Exchanges, CEX, Circuits of Exchange, Constant Product Market Makers, Decentralized Application, Decentralized Blockchain, Decentralized Exchange, Decentralized Exchange (DEX), Decentralized Exchanges, Decentralized Exchanges (DEXes), DeFi Protocols, Dependency, DEX, Digital Exchange, Exchange, Network Science, Networks, Oracles, Payment Channel, Platform, Social Relationships, Stock Exchange, Token Exchange

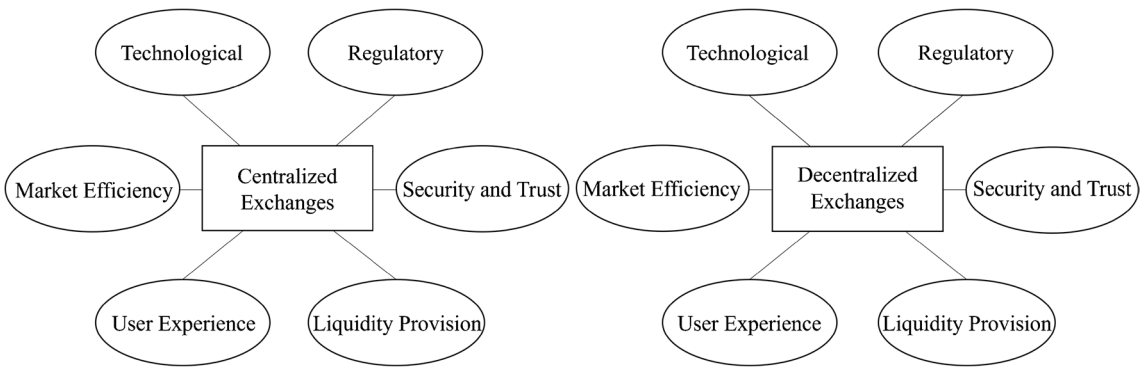

Fig. 4 Superordinate terms for the dimensions of CEX and DEX research

can also be observed. The literature sample includes more than 280 authors from more than 30 different countries, with the majority coming from the USA, followed by the UK, China, Switzerland, and Canada. The diversity of countries of origin, including smaller nations such as St. Lucia, reflects the international importance of research on

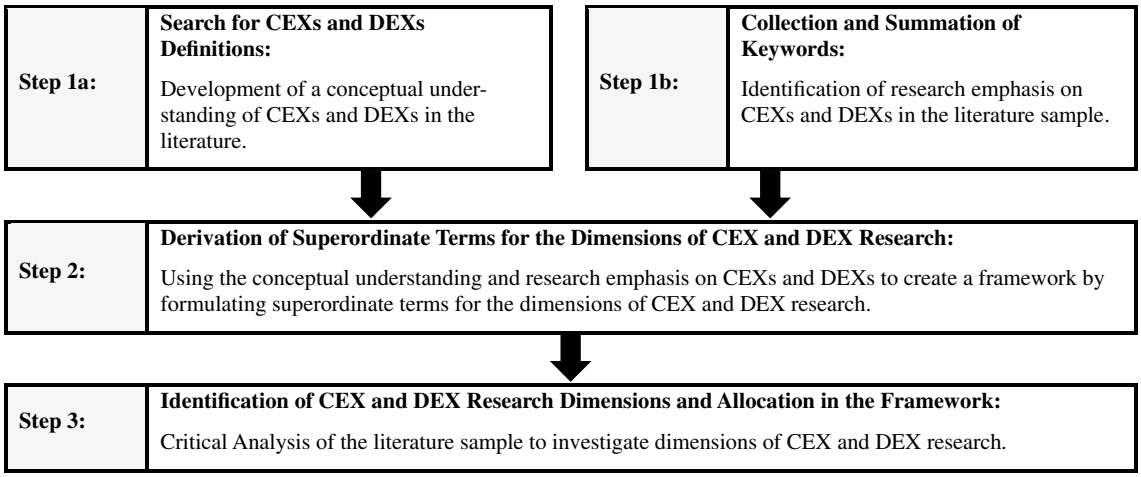

Fig. 5 Summary of the framework development steps

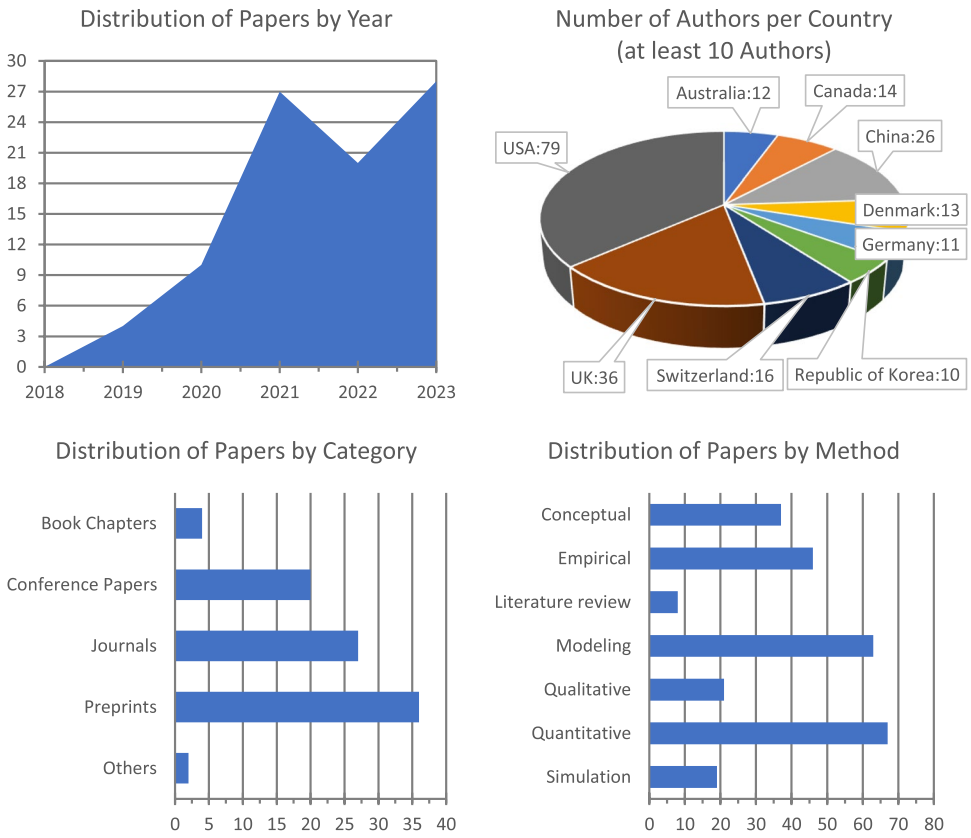

Fig. 6 Descriptive characteristics of the literature sample

CEXs and DEXs and underscores the timeliness and relevance of the topic. All countries of origin with at least 10 authors are also shown in Fig. 6.

The novelty of the papers is also reflected in the type of publication. More than a third of the papers in the literature sample are preprints, most of which have been published either on SSRN or arXiv. While the scientific quality of these papers is not necessarily guaranteed, they have the highest degree of timeliness that a paper can have. In the selection of preprints, care was also taken to ensure their professionality and active further development. In contrast to preprints, and in terms of quantity, the second and third most common types are journal articles and conference papers. They make up more than half of all papers in the literature sample and attest to the scientific quality of the results of the literature search. In addition, the relatively high proportion

of conference papers again supports the timeliness of the subject, as it appears that a significant part of scientific discourse is still conducted within conference communities. Similarly, the limited number of book chapters, let alone book publications, reflects the early stage of research on CEXs and DEXs in cryptocurrency markets.

Finally, the methods of the papers in the literature sample were examined in more detail and classified into seven categories (see also Fig. 6 for reference). These categories do not claim to cover all possible scientific methods, but rather attempt to provide a finer distinction than the classical distinction between quantitative and qualitative methods. Therefore, it is also possible for a paper to be associated with more than one method. Since cryptocurrency markets as a research discipline tend to be at the intersection of several scientific disciplines, I refrain from differentiating the methods of the papers in the literature sample into more distinct theoretical approaches belonging to different scientific disciplines, as such a differentiation may not be helpful and consistent if no more than half of the papers could be categorized by it. However, I acknowledge that there are different, more fine-grained economic approaches (neoclassicism, ANT approach, behavioral economics, …) to the study of markets that could be differentiated and are applied by some of the papers in the literature sample. Looking at the categorization used, the first thing that stands out is the very high proportion of quantitative research compared to qualitative research. More than three quarters of all papers use a mathematical approach, which in most cases is also related to modeling, the second most common research method. The reasons for this can be attributed to the financial nature of the subject matter. As the categorization of keywords has already shown, CEXs and DEXs are primarily financial constructs, and their conception is therefore predominantly quantitative in nature. In addition, there may be a monetary aspect to the design of CEXs and DEXs. The recent success of many companies or projects using CEXs and DEXs has made it easier to investigate the reasons for the success or failure of individual CEX and DEX models. Furthermore, a closer look at the content of the literature sample reveals that, especially in the case of DEXs, their design is still actively researched, with a focus on optimization (e.g., Bergault et al., 2023; Krishnamachari et al., 2021). This thesis is further supported by the high proportion of conceptual methods in the literature sample, which involve the development of innovative approaches that advance current research. These papers are typically highly technical in nature and aim to advance existing approaches through detailed and innovative solutions. Another significant proportion of the papers in the literature sample, in contrast to the methods discussed so far, use existing historical data to gain new insights. These papers often try to identify indicators from market data of a certain period, based on specific events such as the insolvency of the CEX FTX or the collapse of the stablecoin TerraUSD (e.g., Milunovich & Lee, 2022; Vidal-Tomás et al., 2023), with the aim of improving the predictability of the occurrence of such disasters in the future. In contrast to conceptual papers, empirical papers primarily serve the purpose of deriving policy recommendations and concepts, but do not focus on demonstrating their actual implementation. One of the least prevalent methods in the literature sample is qualitative, especially in literature reviews such as this one. While there may be numerous approaches to advancing the current state of research based on the high proportion of conceptual and quantitative research, this advancement is rarely qualitatively grounded, possibly due to the novelty of the research topic. This, in turn, reinforces the purpose of this paper.

Finally, special attention should be paid to those papers in the literature sample that are of high importance for research in the field of CEXs and DEXs, either because of their high number of Google Scholar citations or because they are particularly well-founded through their extensive literature references. The papers with the most Google Scholar citations at the time of the literature review include (in order from most to least cited) Schär (2021), Daian et al. (2020), and Lee (2019). While the early appearance and fundamental orientation of all these papers may be the reason for their high citation rate, in the case of the middle one it is certainly due to the systematic discovery of opportunistic behavior of market participants on the DEXs and the associated practice of front-running at the expense of other market participants, which had not been observed to this extent until then. Nevertheless, all of these articles can be considered highly relevant to the study of CEXs and DEXs. Xu et al. (2023), Qin et al. (2021), and Sai et al. (2021) have the most extensive literature base among the papers in the literature sample. The research approach of all three papers is to conduct a thorough literature review. By delving into the existing literature, they build a solid foundation of knowledge that allows them to place their work firmly in the context of CEX and DEX research. Researchers building on these foundational references can use the insights and critical analysis provided to further their own investigations and contribute to the ongoing advancement of knowledge in the field.

Discussion of the secondary study results

A critical analysis of the papers in the literature sample goes beyond just capturing descriptive characteristics; it delves into the multifaceted landscape of research dimensions on CEXs and DEXs. These dimensions are thoughtfully categorized under their corresponding superordinate terms within the framework and organized in a tabular format, as you can see in Appendix C. However, in an effort to present the

findings in a clear and concise manner and to answer the second research question, I have further condensed the dimensions under each superordinate term into highly aggregated statements, as shown in Table 4. These statements have been carefully formulated to ensure that they encompass the full range of dimensions identified, while maintaining clarity and eliminating redundancy. The exact references are still included in Appendix C. However, for the sake of brevity, I will refrain from including them here. As I proceed, the following sections will examine each dimension in more detail under its respective superordinate term, providing a comprehensive examination and comparison of the dimensions of research on CEXs and DEXs. Based on the results of the secondary analysis, I will then derive precise definitions for CEXs and DEXs, using the newly gained insights and the underlying rationale of these dimensions within the CEX and DEX research landscape.

Looking at CEXs and DEXs from a *technological* perspective, there are distinct features and characteristics that set these two approaches apart. CEXs provide an easy-to-use, centralized platform for cryptocurrency trading. A notable advantage lies in their order-book-based system, which simplifies trading by allowing users to trade cryptocurrencies against traditional fiat currencies untethered from the underlying blockchain (Aigner & Dhaliwal, 2021). This streamlining of the trading process is further supported by the use of "hot" wallets for faster access to funds (Johnson, 2020). It is important to note, however, that CEXs are not without their drawbacks, including occasional technical delays and server outages that can hinder the seamless execution of trades (Lim, 2023). On the other hand, DEXs are emerging as an innovative alternative. They operate without central authorities and enable peer-to-peer trading by using smart contracts for transactions, all without requiring users to relinquish custody of their tokens (e.g., Aoyagi & Ito, 2021). This is a notable advantage, as it aligns with the ethos of decentralization and puts users in control of their assets. DEXs also employ automated market-making functions, typically in the form of constant function market makers (CFMMs), which emphasize efficiency and reduced storage requirements (Angeris, et al., 2022a). Nevertheless, DEXs may face problems related to front-running, where traders with advanced knowledge can use the order of transactions to their advantage (Park, 2021).

From a *regulatory* perspective, CEXs' adherence to federal and state laws seems to provide a sense of legitimacy and security. However, it is important to recognize that these regulations are often focused on traditional financial instruments and may not be perfectly suited to the rapidly evolving landscape of cryptocurrencies. Furthermore, the inherent anonymity of traders and the lack of official oversight create a breeding ground for activities such as wash trading and price manipulation (Alexander et al., 2023). This not only compromises the integrity of these exchanges but also exposes users to a higher risk of financial loss (Aspris et al., 2021). In contrast, DEXs prioritize global accessibility and anonymity, bypassing Know Your Customer (KYC) and Anti-Money Laundering (AML) regulations (Aspris et al., 2021). This approach can be seen as a double-edged sword. On the one hand, it opens the door to a wider range of listings and cross-border trading opportunities (Dewey & Newbold, 2023). On the other hand, it raises concerns about potential money laundering and illicit financial activities (Dai, 2020). The increased anonymity of DEXs may make them an attractive platform for individuals seeking to engage in these activities.

When trading cryptocurrencies, aspects of *security and risk* are of high importance. Traders on CEXs are exposed to a number of vulnerabilities, making it imperative to entrust assets to the infrastructure of the CEX (Lim, 2023). These risks include concerns such as insider trading, hacking incidents, price manipulation, fraud, data breaches, and even outright theft (Johnson, 2020). The need for trust in the operational integrity of the CEX becomes a central element of any transaction. On the other hand, DEXs prioritize security and privacy by eliminating centralized control and providing greater transparency and the ability to retain full custody of assets, effectively reducing counterparty risk (Alexander et al., 2023; Lin, 2019). DEXs facilitate peer-to-peer trading, allowing participants to exchange on-chain assets without relying on a centralized authority (Angeris & Chitra, 2020). However, DEXs have also increasingly become a preferred platform for liquidating stolen tokens due to the anonymity and trustless nature of smart contract transactions (Aspris et al., 2021). This, in turn, presents a different type of security concern within the DEX environment.

Providing liquidity on a CEX and a DEX presents different sets of advantages and disadvantages, each catering to different preferences and risk tolerances. On a CEX, as the primary marketplace, it provides an easy way for users to transfer currencies with high liquidity (Y. Chen et al., 2023b). This liquidity is primarily driven by the constant interaction between buyers and sellers. However, it is worth noting that CEXs, in an effort to maintain market integrity, often impose strict criteria for listing assets (Qin et al., 2021). This can lead to delays in the cryptocurrency listing process and limit the range of tokens available for liquidity provision (Lin, 2019). On the other hand, when it comes to DEXs, liquidity providers take on a unique role. They earn fixed commissions per trade, accepting market risk in the process, making it an enticing opportunity for those who thrive on the decentralization ethos (Aigner & Dhaliwal, 2021). The process of adding tokens to DEXs is significantly more accessible, with fewer barriers compared to CEXs (Dewey & Newbold, 2023). In fact, any token holder can become a liquidity provider simply by depositing tokens. However, the provision of liquidity in

Table 4 Summary of the dimensions of CEX and DEX research

Dimension	Centralized exchanges (CEXs)	Decentralized exchanges (DEXs)
Technological	• CEXs are an order book-based on-ramp facility for trading cryptocurrencies off the blockchain • The blockchain is used as a settlement infrastructure to store information related to the trade • Central institutions facilitate the way of trading by using "hot" wallets • There are known issues of technical delays or server downtime while using CEXs	• DEXs operate without a central authority, facilitate peer-to-peer trading by using smart contracts for transactions, and have automated market-making capabilities • They allow users to trade without relinquishing custody of their tokens through a novel market design • DEXs typically use constant function market makers (CFMMs) instead of order books • DEXs offer computational efficiency and reduced storage requirements but may face challenges related to front-running and atomic risk-free exploits
Regulatory	• In some countries, CEXs are essentially unregulated • This circumstance leads to wash-trading, price manipulation, or higher risk of loss and is caused by the lack of an external regulatory party and trader anonymity • However, as a basic requirement, CEXs must comply with relevant federal and state laws	• DEXs offer global accessibility and anonymity, bypassing KYC and AML regulations, leading to a wider range of listings and concerns about money laundering and criminal financing • DEXs provide a trading venue for assets that may not meet the requirements of a centralized exchange • The growing importance of DEXs complicates financial regulation, as they often operate with weak or no legal identities, evading regulation
Security and risk	• CEXs are exposed to many risks and criminal activities for traders such as insider trading, hacking, price manipulation, fraud, data breaches or theft • Traders rely on their trust in the CEXs infrastructure in order to transfer and manage their assets	• DEXs enhance security and privacy by eliminating centralized control, promoting transparency, and allowing users to retain custody, thereby reducing counterparty risk • Participants can trade on-chain assets without having to trust a centralized authority • DEXs have become a choice for liquidating stolen tokens and offering trustless transactions through smart contracts
Liquidity provision	• As a primary marketplace, CEXs provide an easy way to transfer currencies and offer higher liquidity due to the continuous engagement between buyers and sellers • CEXs have specific criteria for listing assets, which can lead to delays in the process of listing cryptocurrencies	• Liquidity providers on DEXs earn fixed commissions per trade and take on market risk, making it an attractive opportunity • There are far fewer barriers to adding tokens to DEXs • Any token holder can become a liquidity provider by depositing tokens • Liquidity provision in AMMs is determined by the ratio of tokens in the pool and contributes little to price discovery
User experience	• In the basic operation of the CEX, users transfer their assets from a user wallet to a wallet managed by the CEX. This has both advantages and disadvantages • Some advantages are relatively fast transaction speeds, enhanced trading features, and simplified user experience • Some disadvantages are high transaction fees, limited transparency, and registration procedures	• DEXs allow users to exchange assets without intermediaries, ensuring that trades are settled on the public ledger • DEXs are vulnerable to transaction-ordering attacks • Users of automated market makers (AMMs) do not require specific pairings to complete trades • DEXs may reduce trading costs, especially for large orders
Market efficiency	• Despite their relative efficiency, CEXs can be plagued by limited trading volume and liquidity • Prices on CEXs are determined by the order book trading process and are entirely under the control of the traders, resulting in significant price volatility • CEXs require the involvement of active market makers and allow for a wide range of cryptocurrency transactions	• DEXs aid in price discovery by facilitating the listing and trading of new tokens • Prices on DEXs are often less efficient, can be inconsistent, and vary between different DEXs • DEXs primarily support crypto-to-crypto transactions and rely on arbitrageurs to balance prices • DEXs allocate risk more efficiently among traders with different risk preferences, resulting in unique trading profits

AMMs on DEXs works differently. It is determined by the ratio of tokens in the pool and does not actively contribute to price discovery (Y. Chen et al., 2023b). Unlike CEXs, where price formation and especially discovery is primarily driven by order book dynamics, DEXs rely on the inherent token ratios in the pools.

Trading on a CEX is, from a *user's experience*, a structured process in which assets move from a user wallet to a wallet managed by the exchange (Victor & Weintraud, 2021). This arrangement has both advantages and disadvantages. On the positive side, CEXs offer relatively fast transaction speeds, enriched trading functionalities, and a user-friendly interface (Lim, 2023). These aspects make for an efficient and convenient trading experience, allowing users to execute their transactions with ease. However, trading on CEXs is also associated with high transaction fees, which reduce the overall returns (Dai, 2020). In addition, CEXs tend to have limited transparency. Users may find it difficult to obtain comprehensive information about the inner workings of the exchange, which can lead to traders' discomfort. In addition, CEXs often require complex registration procedures, which can deter potential users and complicate the onboarding process (Lin, 2019). In contrast, DEXs allow users to engage in asset exchanges without the involvement of intermediaries and guarantee that transactions are recorded on a public ledger (Aspris et al., 2021). This open and decentralized approach ensures a transparent and secure environment for users. However, DEXs are susceptible to transaction-ordering attacks, which can affect the order and thus the profitability of trades (Han et al., 2022). AMM aggregators provide flexibility by not requiring specific pairings for transactions, but they can occasionally lead to suboptimal pricing (Park, 2021). Despite these challenges, DEXs offer an attractive advantage in reducing trading costs, especially for large orders (Lin, 2019).

Finally, *market efficiency* at CEXs depends on several key factors. First and foremost, despite their comparative efficiency, CEXs often face constraints, particularly limited trading volume and liquidity. This can hinder the seamless execution of trades, making them less efficient at handling large order flows (Wang & Krishnamachari, 2022). In addition, price determination on CEXs relies solely on the order book trading process and trader control, resulting in potentially significant price volatility (Ciampi et al., 2022). The control factor can lead to potential price manipulation and erratic fluctuations that can undermine market stability. Conversely, CEXs also have some advantages. They encourage the active participation of market makers, an essential component in maintaining order flow and liquidity. This, in turn, encourages a diversified range of cryptocurrency transactions and provides traders with a degree of predictability and ease in executing their trades (Schär, 2021). DEXs, on the other hand, contribute to price discovery by facilitating the listing and trading of new tokens (Aspris et al., 2021). However, prices on DEXs tend to be less efficient, resulting in inconsistencies and variations across DEX platforms (Barbon & Ranaldo, 2021). This inconsistency can pose challenges for traders seeking price transparency and accurate execution. DEXs primarily support crypto-to-crypto transactions and rely on arbitrageurs to balance prices, which can lead to longer execution times and potential inefficiencies (Krishnamachari et al., 2021). However, DEXs do offer unique benefits by more efficiently allocating risk among traders with different risk preferences, resulting in distinct trading advantages.

In summary, the findings on the dimensions of CEX and DEX research, as determined in this manner and viewed from multiple perspectives, can be summarized as follows, in accordance with the previously explored definitions and keywords identified to answer the first research question:

Centralized exchanges (CEXs) are cryptocurrency trading platforms that provide a user-friendly and centralized environment for buying and selling digital assets. They use an order book-based system to simplify the trading process and allow users to trade cryptocurrencies against traditional fiat currencies. However, technical delays and server outages can occur, potentially disrupting the smooth execution of transactions. CEXs primarily comply with federal and state regulations, providing users with a sense of authenticity and security. However, the anonymity of traders on some CEXs raises concerns about activities such as wash-trading and price manipulation, which can undermine the integrity of these exchanges.

Decentralized exchanges (DEXs) operate without a central authority and enable peer-to-peer cryptocurrency trading by using smart contracts for transactions, allowing users to retain custody of their tokens. DEXs include automated market-making functions, typically in the form of constant function market makers (CFMMs), which increase efficiency and reduce the need for extensive on-chain storage. DEXs face challenges such as front-running, where traders with advanced knowledge take advantage of the transaction order. In addition, they prioritize global accessibility and anonymity, bypassing KYC and AML regulations, which can expand the scope of listings but also raise concerns around money laundering and illicit financial activity.

Open research questions and future directions

Within the vast landscape of cryptocurrency exchanges, it has become clear that researchers are actively engaged in exploring a variety of aspects, each of which offers unique insights. One of the key areas of research is the concept of pricing functions that underpin the operation of these exchanges (e.g., Park, 2021, 2023). These vary not only

between CEXs and DEXs but also within the emerging category of HEXs, such as EtherDelta, dYdX, and IDEX (dos Santos et al., 2022; Falakshahi et al., 2021; Koroļkovs & Kodors, 2022; Schär, 2021). In Fig. 7, I provide a visual systematization of the different exchanges and categorize them according to their pricing functions mentioned in the literature sample to answer the third research question. In addition, I also provide implementation examples that exist in cryptocurrency markets for each different implementation variant. To the best of my knowledge, it is the first differentiation of such pricing functions and therefore may not capture all possible concepts already implemented in practice. However, it attempts to capture the most prominent ones.

As shown in the figure, the pricing mechanisms of an exchange can first be differentiated by considering whether price discovery takes place on-chain, specifically on a cryptocurrency's blockchain using smart contracts, or off-chain. While the on-chain method has the well-known advantages and disadvantages associated with a blockchain, such as a high level of transparency but increased storage costs and slower transaction processing, an off-chain implementation offers speed but tends to be more centralized and less transparent. In addition to the well-known central limit order book (CLOB), which "is a method to facilitate an exchange between market participants, where two sorted lists are maintained including the price and amount that traders are willing to buy (bid side) or sell (ask side)" (Khakhar & Chen, 2022, p. 1), and traditional auction trading, a family of pricing functions based on the logarithmic market scoring rule developed by Hanson (2003, 2007) has received increasing attention in research. These pricing functions were first proposed for implementation on Ethereum by Vitalik Buterin in a 2016 Reddit post (Buterin, 2016) and can be subsumed under the term of AMMs. Unlike CLOB pricing functions and auctions, which are less prepared for on-chain use due to the associated blockchain storage costs (Zatonatska et al., 2022), but can still be implemented on-chain, AMMs are only implemented on-chain. Therefore, by definition, they are used exclusively by HEXs and DEXs. In the category of AMMs, there are a variety of models, such as constant function market makers (CFMMs), which further branch into liquidity sensitive logarithmic market scoring rule (LS-LSMR), constant product market maker (CPMM), constant sum market maker (CSMM), constant mean market maker (CMMM), and proactive market maker (PMM). Although these models differ in minor details, they all aim to optimize liquidity provision and price discovery in the context of DEXs. The diversity of approaches and methods is a testament to the volatility of concepts in this area of research. Many trades on DEXs currently occur under suboptimal conditions (Berg et al., 2022), imposing negative externalities on other DeFi applications (Capponi & Jia, 2021). While the current research focus is on the development of new on-chain pricing mechanisms (Bergault et al., 2023; Krishnamachari et al., 2021), off-chain settlement is increasingly taking a back seat, and thus, a clear research need can be identified.

DEXs are still dependent on external prices (Jensen et al., 2021a; Sylvester et al., 2022), which is why there is a growing focus on improving market efficiency and price discovery of DEXs (e.g., Alexander et al., 2023; Barbon & Ranaldo, 2021; Berg et al., 2022; Pourpouneh et al., 2020). New and innovative pricing functions are already being actively researched (e.g., Y. Chen et al., 2023b; Kim et al., 2022; Lin, 2019; Schär, 2021). One solution could be the use of oracles (Berg et al., 2022; Dave et al., 2021), which is still an object of active development. Another topic of particular interest in current research is the design of front-running resistant AMMs (e.g., Bartoletti et al., 2022; Ciampi et al., 2022; Zhou et al., 2021a, b). Front-running, or the act of exploiting advance knowledge of upcoming transactions, remains a concern in DeFi. Researchers are actively investigating ways to improve security mechanisms to protect users from such unfair trading practices. The sequencing of transactions within DEXs is also of paramount

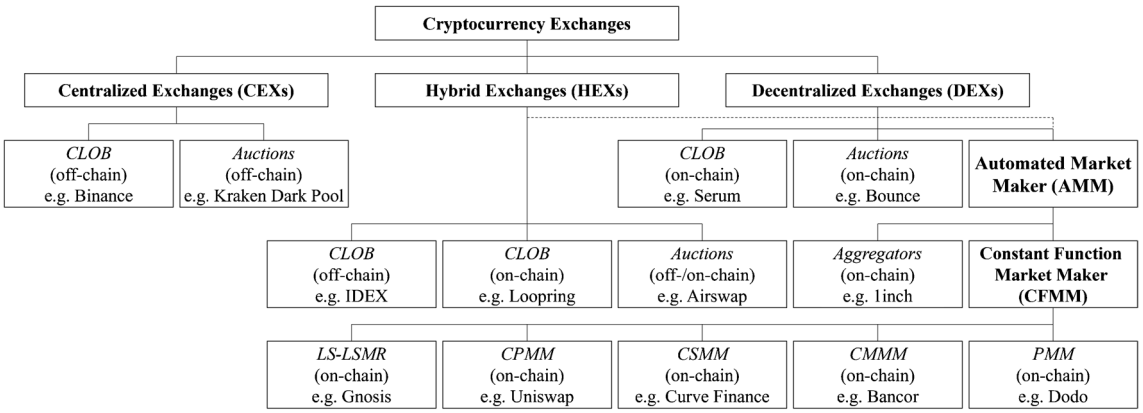

Fig. 7 Pricing functions of cryptocurrency exchanges

importance, as it affects the fairness and efficiency of order execution. Researchers are actively working to improve the algorithms that govern the execution of trades in DEXs (e.g., Gong & Kate, 2023). It is important to make DEXs resilient to order-routing and front-running in order to maintain their competitiveness with CEXs. For this reason, future research, while already very active, needs to focus on advancing existing approaches to ensure this.

AMMs are at the forefront of research and offer the potential to provide liquidity more efficiently than CEXs. Liquidity providers on DEXs must balance potential adverse selection with fee income, raising questions about their strategies and returns (Lehar & Parlour, 2021). Quantifying the returns of liquidity providers is another topic that has received much attention in the literature (e.g., Aigner & Dhaliwal, 2021; Bergault et al., 2023; Khakhar & Chen, 2022; Milionis et al., 2023b). Among other things, liquidity provision on DEXs has been found to be influenced by other liquidity providers (Aoyagi, 2020) and other markets (e.g., CEXs) (Aoyagi & Ito, 2021). However, it remains to be clarified to what extent providing liquidity on DEXs is advantageous compared to providing liquidity on CEXs or not providing liquidity at all. For this reason, there are already approaches to measure the returns of liquidity providers on DEXs (e.g., Milionis et al., 2023c). However, most of them are still the subject of open discussion, so there is still room for further approaches to measuring the returns to providing liquidity on DEXs that can be explored in future research.

While adoption of DEXs is gradually increasing, it is important to note that it is evolving at a relatively slow pace. Researchers are actively investigating strategies to accelerate adoption and make DEXs more user-friendly and accessible (Heimbach et al., 2021). For many of them, the prevailing shift toward centralization is a major concern (Vidal-Tomás et al., 2023). For example, some of them observe a shifting behavior of traders switching between DEXs and CEXs in response to new token listings (Aspris et al., 2021) or a trend toward the monopolization of individual CEXs in general (Vidal-Tomás et al., 2023). The dominance of a small number of exchanges in handling a significant portion of transactions underscores the importance of exploring mechanisms to maintain a decentralized ecosystem (Sai et al., 2021). A significant amount of research focuses on Uniswap as an empirical starting point for DEX research, taking advantage of its position as the leading DEX (e.g., Fritsch, 2021; Ghazzawi & Yanovich, 2023; Koroļkovs & Kodors, 2022; Lo & Medda, 2020; Xia et al., 2021). The detection and prevention of fraudulent tokens in platforms such as Uniswap and the broader DeFi ecosystem remain areas of active research to improve the security and integrity of these platforms (Trozze et al., 2023; Xia et al., 2021). CEXs, acting as *choke points*, can play a critical role in detecting criminal activity within the DeFi/DEX space by enforcing Know Your Customer (KYC) regulations (Caliskan, 2020; Trozze et al., 2023). However, because not all CEXs comply with the regulatory requirements imposed on them, or deliberately move their operations overseas where there are little to no requirements, CEXs often fall victim to phishing or other cybersecurity attacks, often with catastrophic consequences for their users. As a result, the research community is focusing on developing indicators for CEXs that can predict and prevent insolvency, recognizing the potential impact on users and the overall market. This emphasis on security and compliance is critical to maintaining the integrity of these platforms and reinforces the need for further research in this area.

The presented and identified research focus areas are only a glimpse of possible open research questions and future research directions perceived in the area of CEXs and DEXs. Especially with regard to the dimensions of user experience and technological aspects, there is still a need for optimization, which requires further research. The potential research directions are thus diverse, multi-perspective, and interdisciplinary, leaving ample room for further development.

Conclusion

This paper conducts a comprehensive literature review of CEXs and DEXs to provide a thorough analysis of their respective research dimensions. After identifying definitions and keywords, a framework is systematically constructed and enriched with appropriate superordinate terms to support this endeavor. The analysis reveals a diverse range of current research in this systematic literature review, with notable quantitative and conceptual contributions from different countries. This compilation of research highlights the contemporary relevance of the topic and provides a multifaceted view of the field. Within the dimensions of research on centralized and decentralized cryptocurrency exchanges, the secondary analysis reveals two distinct market models that exhibit significant differences. These distinctions provide valuable insights into the diverse and complex world of crypto exchanges. The formulation of comprehensive definitions in this context provides a strong foundation for future research. Current research trends go beyond the development of pricing functions for CEXs, HEXs, and DEXs. These topics include front-running in decentralized markets, optimizing transaction sequencing, quantifying returns for liquidity providers, and addressing regulatory concerns such as preventing fraudulent tokens and regulating cryptocurrency exchanges.

While this literature review has taken a systematic and comprehensive approach, it is not without limitations. Despite efforts to cast a wide net by including multiple

databases and outlets, the possibility of missing noteworthy papers remains. The selection and extraction process, which was guided by specific criteria, nevertheless retained elements of subjectivity. In addition, the quality and relevance of the literature serve as inherent limitations. The constant evolution of the cryptocurrency exchange landscape, combined with the mismatch between the pace of academic research and market operations, could potentially lead to the neglect of inventive methods that have not been subject to academic scrutiny. These aspects underscore the dynamic nature of the cryptocurrency exchange sphere and the urgent need for ongoing research and analysis.

The identified research directions are relevant not only for researchers, but also for practitioners, as they actively contribute to the evolution of CEXs and DEXs through the creation of innovative protocols. Therefore, all the research questions and directions mentioned in this paper can also be seen as an inspiration for practitioners to invent new, innovative protocols that try to address the problems and issues that currently persist in cryptocurrency markets, thereby advancing research in this area as well.

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