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DECENTRALIZED FINANCE – A SYSTEMATIC LITERATURE REVIEW AND RESEARCH DIRECTIONS

Research Paper

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Abstract

Decentralized Finance (DeFi) is the (r)evolutionary movement to create a solely code-based, intermediary-independent financial system—a movement which has grown from $4bn to $104bn in assets locked in the last three years. We present the first systematic literature review of the yet fragmented DeFi research field. By identifying, analyzing, and integrating 83 peer-reviewed DeFi-related publications, our results contribute fivefold. First, we confirm the increasing growth of academic DeFi publications through systematic analysis. Second, we frame DeFi-related literature into three levels of abstraction (micro, meso, and macro) and seven subcategories. Third, we identify Ethereum as the blockchain in main academic focus. Fourth, we show that prototyping is the dominant research method applied whereas only one paper has used primary research data. Fifth, we derive four prioritized research avenues, namely concerning i) DeFi protocol interaction and aggregation platforms, ii) decentralized off-chain data integration to DeFi, iii) DeFi agents, and iv) regulation.

Keywords: Decentralized Finance, DeFi, Literature Review, Research Directions, Blockchain.

1 Introduction

With the intention to eliminate the need for financial intermediaries by creating a solely code-based, openly accessible, and transparent financial system, Nakamoto (2008) invented the Bitcoin blockchain—the first consensus-governed, decentralized database of cryptographically linked blocks storing and enabling borderless, trustless, all-time available, and digitally signed P2P-transactions. With the Turing-complete script language of the Ethereum blockchain, Buterin (2013) decisively evolved the idea and presented the first practical implication of 'smart contracts' (i.e., code-based agreements executed without human intervention), hence providing the technical foundation for 'Decentralized Finance (DeFi)'—a finance ecosystem enabling complex financial products and transactions in a trustless and borderless manner (e.g., lending/borrowing, derivatives (trading) and borderless stable assets). That this ecosystem is not only an idealistic idea of blockchain utopians but is to be taken seriously is, as of Nov, 5th 2021, reflected in i) Bitcoin's $1,150bn market capitalization (CoinMarketCap, 2021a) exceeding the combined $1,135bn market worth of the world's three highest valued banks[1], ii) the market capitalization of the main DeFi blockchain Ethereum with $530bn—surpassing that of the highest valued bank[1] and growing tenfold within one year (CoinMarketCap, 2021b), as well as iii) the Total Value Locked in DeFi applications—growing by 26 times in three years from $4bn to $104bn (DeFi Pulse, 2021).

[1] JPMorgan Chase with $503bn, Bank of America with $393bn, and ICBC with $239bn (CompaniesMarketCap, 2021).

To date, the following papers have provided overviews of the DeFi space: Chen and Bellavitis (2020), Schär (2021), and Jensen et al. (2021) characterize the structure, advantages, challenges, and use cases of DeFi from their own point of view and experience, i.e., not following a systematic, literature-guided approach. Bartoletti et al. (2020b) and Cousaert et al. (2021) present 'Systemizations of Knowledge (SoKs)' for the DeFi subspaces of lending protocols and yield aggregators, respectively. They thereby pursue a mixed approach of synthesizing academic literature and conducting own subspace analyses. Werner et al. (2021) conduct a SoK for the entire DeFi space, however, focusing on security challenges and delineating them into technical and economic ones. Systematic literature reviews, on the other hand, e.g., by Pal et al. (2021) and Ali et al. (2020), have not focused on DeFi but rather on finance blockchain applications in general, i.e., including applications still involving intermediaries. Hence, by the time of our writing and to the best of our knowledge, no study has systematically reviewed the state of increasing academic DeFi contributions—a review highly required to structure this fragmented field of research.

This paper closes this gap and identifies 83 peer-reviewed DeFi-related papers as a basis to address three research questions (RQ): RQ1) How can DeFi literature to date be structurally framed and which research methods and blockchain systems have scholars focused on? RQ2) Which results and insights can be synthesized from the current state of research? RQ3) Which research avenues can be derived? We thereby help scholars in gaining a systematic and cross-disciplinary overview of DeFi-related literature to date including non-conclusive research results, understudied areas, and underemployed research methods. Specifically, our paper offers five contributions: First, we confirm through systematic analysis that the number of academic DeFi publications is rapidly increasing. Second, we present the first systematically developed framework of DeFi literature: I.) the micro-level with research on financial a.) smart contracts, b.) tokens, and c) applications; II.) the meso-level with papers on a.) DeFi patterns within and b.) scaling solutions beyond single-chain systems; and III.) the macro-level with holistic research on a.) the DeFi ecosystem (e.g., DeFi participants) and b.) its wider societal impact (e.g., on the legacy financial system and regulatory bodies). Third, we find that scholars have focused on the Ethereum blockchain followed by blockchain system-independent research. Fourth, we show that prototyping/ proof-of-concepts (PoCs) are the dominating research method in this new field. Fifth, we suggest four research avenues to further support DeFi advancements.

The remainder of this paper proceeds as follows: Section 2 provides the theoretical background and research methodology. Section 3 presents the literature framework, applied research methods, and blockchain focuses (RQ1) as well as the synthesis of the current state of DeFi research (RQ2). Section 4 suggests future research avenues (RQ3). Section 5 discusses limitations and concludes.

2 Background and Research Methodology

2.1 Narrowing of the term 'DeFi' and the scope of this literature review

Based on several scholars' definition, we find that 'DeFi' refers to finance protocols i) built with '**smart contracts'** (Gudgeon et al., 2020a; Zetzsche et al., 2020; Jensen et al., 2021) ii) which are '**trustless**' (Chen and Bellavitis, 2020; Kumar et al., 2020; Werner et al., 2021), i.e., functioning without intermediaries (trusted third parties), and iii) developed on '**permissionless, public blockchains**' (Chen and Bellavitis, 2020; Schär, 2021; Wang, 2020; Popescu, 2020). Figure 1 illustrates the scope of our review, whereas the following in-depth descriptions help to discriminate DeFi from non-DeFi but blockchain- and finance-related application fields:

'Smart contract-based': DeFi stems from but needs to be delineated from the field of non-smart contract based crypto-finance. Only with the introduction of smart contracts—programmatically enforced agreements (Schär, 2021)—the development of conditional, complex financial services was enabled. Similar delineation logic applies to related fields of (non-smart contract enabled) blockchain-native cryptocurrency specifics, e.g., price building of Bitcoin, or crypto-asset trading strategies.

'Trustless': While cryptocurrencies were invented to replace trusted third parties, in fact, most volume is stored and traded on 'centralized exchanges (CEXs)' (Cong et al., 2019), i.e., undermining the disintermediation aim (Zamyatin et al., 2019). Equally, the enhancement of banks' processes, new financial services still involving intermediaries (e.g., physically-, third party-backed stablecoins), as well as digital currencies issued by central banks or other third parties are not part of our definition of DeFi.

'Permissionless, public blockchains': DeFi is meant to be accessible for everyone, i.e., built on openly accessible ('permissionless'), public blockchains. Permissioned systems, on the other hand (i.e., private or consortium blockchains), do not only prevent the accessibility for everyone but also contradict decentralization principles since system participants can change the rules of the blockchain, revert transactions, etc. (Buterin, 2015).

Further, we exclude research related to token investments/ offerings, as this field has been studied in broader depth with own literature reviews (see Moxoto et al. (2021)).

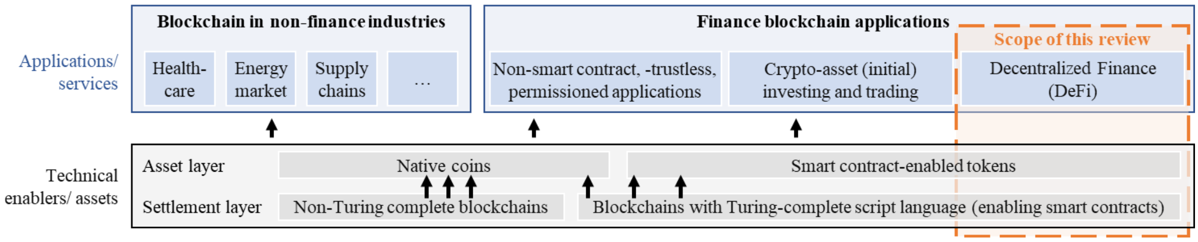

Figure 1. Schematic illustration of the scope of this literature review.

2.2 Research methodology

To ensure a high-quality review, we followed the research methodologies for systematic literature reviews by Webster and Watson (2002), Levy and Ellis (2006), and vom Brocke et al. (2015). Our process to identify relevant literature is illustrated in Figure 2. As suggested by vom Brocke et al. (2015), our search involved several databases and a combination of search strategies. In total, we screened 7 databases and supplemented a cross-check on Google Scholar. In each database, we conducted a full text search for "Decentralized Finance", "Decentralized Banking" (a synonym) or "Decentralized Exchanges" (DEX) (a delineator from the research field of cryptocurrencies, largely traded on CEXs) in combination with "Blockchain". As outlined by vom Brocke et al. (2015, p. 210), "the number of retrieved publications can be small when new types of technologies ("buzzwords") are studied, which is not uncommon in an IT-oriented discipline […], and it can be large when it turns out that these new technologies have already been studied under different labels". Hence, to not neglect relevant research before the term DeFi entrenched, we added a 'Title, Abstract and Keyword' search for the terms "Smart Contract?", "Financ*" and "Blockchain". In our Google Scholar cross-check, we searched for "Decentralized Finance" or "DeFi" in the title or abstract. We only included peer-reviewed publications to ensure that all sample papers were subject to quality controls (Davison et al., 2005). Moreover, we included English papers from journals and conferences (or symposiums), as the latter play an important role in the research dissemination process in fast-moving information system fields (Bandara et al., 2011; vom Brocke et al., 2015). Of the 1006 papers matching our criteria, we excluded 228 duplicates. From the remaining 778 papers, we first excluded 549 non-blockchain or non-finance focused papers which also comprised cross-industry research such as on blockchain, smart contract, and governance specifics without a dedicated finance angle. Yet, we acknowledge that those fields are interdependent with DeFi. Second, we excluded 162 papers whose research scope did not cohere to the in section 2.1 discussed DeFi-scope. The resulting list of 67 articles was complemented by 16 articles from backward and forward searches as suggested by Webster and Watson (2002) and Levy and Ellis (2006).

As seen in Figure 3, 55 of the 83 papers were published only in 2020 or the first half of 2021. Early papers were mostly published through conferences or symposiums (led by IEEE and ACM conferences), confirming their importance for research dissemination in fast moving fields as DeFi.

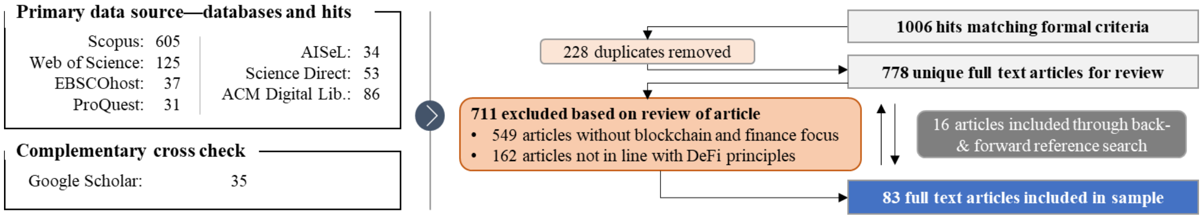

Figure 2. Literature identification and selection process.

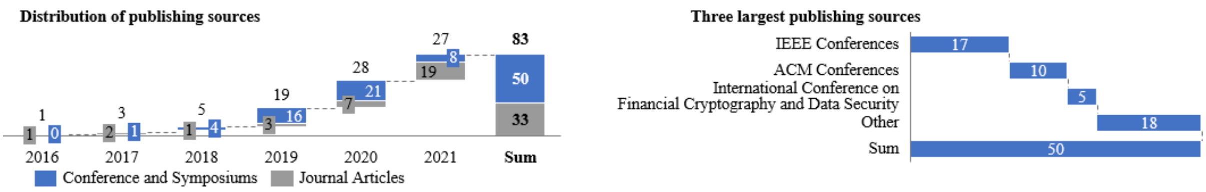

Figure 3. Overview of publishing sources.

Moreover, 63 out of the 83 publishing sources can be (co-)allocated to the subject area of 'Computer Science'. Of those 63 publishing sources, ~10 each are also applicable to the subject areas of 'Economics, Econometrics, and Finance', 'Business Management and Accounting', and 'Decision Science'. Of the remaining 20 sources, 'Business, Management and Accounting' (~10 papers) as well as 'Social Sciences' and 'Economics, Econometrics, and Finance' (~7 papers each) constitute the largest subject areas in accordance with the Scopus data based SCImago Journal Ranking (SCImago, 2020). This width in subject areas affirms that DeFi literature can be considered a cross-disciplinary research field.

To unbiasedly integrate, describe, and summarize the identified 83 papers in a systematic and replicable approach, we followed the literature review specific coding guidelines by Wolfswinkel et al. (2013).

3 Results

3.1 Literature framework overview

Based on the coding analysis, we frame the current academic DeFi-literature into three levels of abstraction/ perspective and seven subcategories. The framework overview and content-focuses for each of the seven subcategories can be found in Figure 4. On the I.) 'micro-level', the largest category with 35 papers (see Table 1), academics study aspects of individual components of the DeFi landscape, namely a.) smart contract (language), b.) tokens, and c.) DeFi protocols. With 17 papers, prototype buildings/ PoCs are the most prominent research methodology on the micro-level. Further, in line with real-world applications (Chen and Bellavitis, 2020), scholars largely focus on the Ethereum blockchain (21 papers). On the II.) 'meso-level', authors study characteristics within a single blockchain system (e.g., identifying Ponzi scheme patterns) mainly by using empirical Ethereum network data (15 out of 17 papers), or research on opportunities to scale DeFi beyond a single-chain system, namely looking at cross-chain-interoperability or decentralized off-chain data integration possibilities for DeFi applications (13 papers). Lastly, on the III.) 'macro-level', authors take a holistic view either by analyzing the entire DeFi ecosystem, e.g., structuring DeFi advantages or use cases (8 papers in total), or the ecosystem's broader implications on society (e.g., the legacy financial system) and subsequent need for DeFi regulation (10 papers). Studies on the macro-level are mostly blockchain-system independent (10 papers) and hence less Ethereum-focused and mainly use a descriptive research approach (14 papers).

Overall, with 27 papers, prototypes/ PoCs represent the most applied research method, of which 25 papers can be co-allocated to the subject area of 'Computer Science' and the other two to 'Engineering'.

Only one paper in our sample, on the other hand, has collected primary data for research. With 49 papers, Ethereum represents the blockchain with most research focus. A comprehensive overview of papers, research methodologies, and blockchain focuses per (sub-)category can be found in Table 1. In the following subsections, we present the in-depth content synthesis for each (sub-)category.

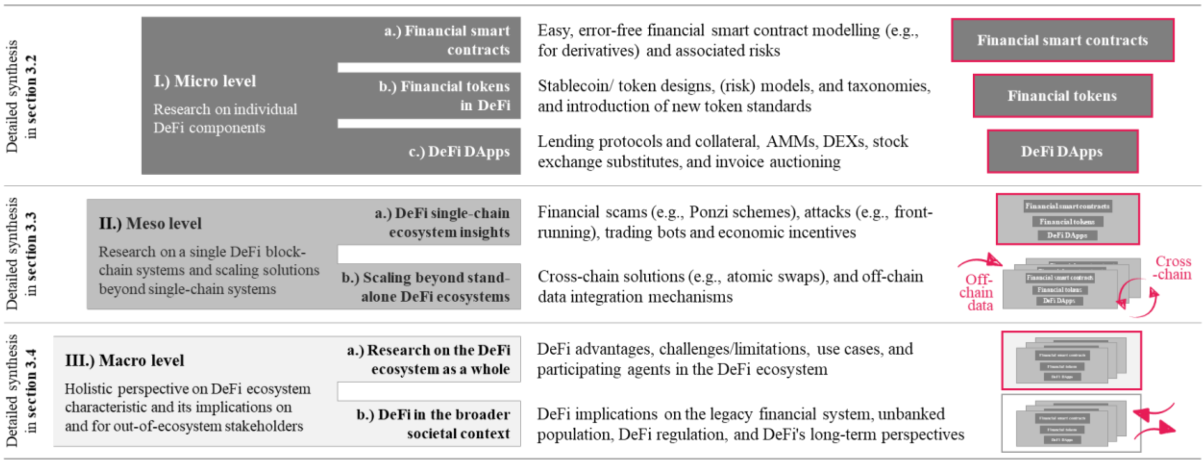

Figure 4. DeFi literature framework.

Note: Multiple research methodologies per paper possible; full table can be provided upon request

Framework (sub-) categories	Categorized papers	# total paper	Empirical - Primary data	Empirical - Secondary data	Prototype / PoC	Theoretical (modelling)	Descriptive conceptualization	Ethereum	Other (e.g. Cardano)	Multiple/ system-independent
Total		**83**	**1**	**21**	**27**	**20**	**20**	**49**	**2**	**32**
I.) Micro level		**35**	**-**	**3**	**17**	**11**	**5**	**21**	**2**	**12**
a.) Financial smart contracts	Arusoaie (2021); Biryukov et al. (2017); Clack (2018); Egelund-Müller et al. (2017); Perera et al. (2020); Seijas et al. (2020); Seijas and Thompson (2018); Skotnica and Pergl (2020); Spiridonov (2021)	**9**	-	-	6	2	1	5	1	3
b.) Financial tokens in DeFi	Davydov et al. (2019); Hu et al. (2019); Klages-Mundt et al. (2020); Liu et al. (2020); Matsuura (2019); Moin et al. (2020); Pernice et al. (2019); van der Merwe (2021)	**8**	-	2	2	2	2	3	1	4
c.) DeFi DApps (decentralized applications)	Angeris and Chitra (2020); Angeris et al. (2019); Bansal et al. (2019); Bartoletti et al. (2021); Kim (2021); Grant et al. (2020); Gudgeon et al. (2020); Guerar et al. (2020); Guerar et al. (2019); Harz et al. (2019); Lin et al. (2019); Okoye and Clark (2019); Pop et al. (2019); Reno et al. (2021); Sridhar et al. (2020); Tien et al. (2020); Tsai et al. (2020); Yang et al. (2019)	**18**	-	1	9	7	2	13	-	5
II.) Meso level		**30**	**-**	**16**	**10**	**8**	**1**	**20**	**-**	**10**
a.) DeFi single-chain ecosystem insights	Bartoletti et al. (2020); Bian et al. (2021); Chen et al. (2021); Chen et al. (2018); Chen et al. (2019b); Daian et al. (2020); Eskandari et al. (2020); Gudgeon et al. (2020); Jung et al. (2019); Lou et al. (2020); Perez et al. (2020); Struchkov et al. (2021); Tien et al. (2020); Victor and Weintraud (2021); Wang et al. (2021a); Wang et al. (2021b); Wu et al. (2021); Zhou et al. (2021)	**17**	-	14	1	3	1	15	-	2
b.) Scaling beyond stand-alone DeFi ecosystems	Borkowski et al. (2019); George and Lesaege (2020); Han et al. (2019); Herlihy (2018); Kumar et al. (2020); Lei et al. (2019); Li et al. (2019); Park et al. (2020); Rueegger and Machado (2020); Shekhawatu et al. (2021); Tefagh et al. (2020); Wang et al. (2021); Zamyatin et al. (2019)	**13**	-	2	9	5	-	5	-	8
III.) Macro level		**18**	**1**	**2**	**-**	**1**	**14**	**8**	**-**	**10**
a.) Research on the DeFi space as a whole	Chen et al. (2020); Jensen et al. (2021); Lockl and Stoetzer (2020); Popescu, 2020; Schär (2021); Stepanova and Eriņš (2021); Smith (2021); Zhang (2021)	**8**	1	-	-	-	7	5	-	3
b.) DeFi in the broader societal context	Abdulhakeem and Hu (2021); Clippinger (2016); Ellul et al. (2020); Duran and Griffin (2021); Guseva (2021); Hütten (2019); Johnson (2021); Larios-Hernández (2017); Paech (2020); Zetzsche et al. (2020)	**10**	-	2	-	1	7	3	-	7

Table 1. Paper sample, research methods, and blockchain focus per framework (sub-)category.

3.2 Literature synthesis—Micro level

The 35 papers on the micro-level study aspects of individual components of the DeFi landscape. We cluster this level further into three subcategories differentiated by topic focus: a.) '**Financial smart contract research**', i.e., investigating financial smart contract language designs; b.) '**Financial tokens in DeFi**', i.e., studying the store-of value forms built with smart contracts; and c.) '**DeFi DApps**', i.e., researching and building prototypes of DeFi services. With overall 18 papers, the latter subcategory present the largest one in our framework.

Financial smart contracts: The technical foundation of DeFi is constituted by the underlying blockchain or 'settlement layer' (Schär, 2021) and the incorporated feature of smart contracts. An important question posed here by the 9 papers in our sample, is how complex financial contracts from the traditional world can efficiently, easily, and error-free be transferred to and executed in smart contract programming language (e.g., Skotnica et al. (2020) and Spiridonov (2021)) such that finance managers can focus on the contract specification rather than coding specifics (e.g., Arusoaie (2021) and Spiridonov (2021)). Authors in this field build on pre-blockchain work, which enabled the transition of financial agreements written in natural language towards formal contract languages—also called domain-specific languages (DSLs), pioneered by Arnold et al. (1995) and Jones et al. (2000) (Egelund-Müller et al., 2017). Transferring the idea to the world of smart contracts, several new DSLs for financial contracts such as derivatives have been developed using a PoC research methodology: *Marlowe* for the Cardano chain (Seijas and Thompson, 2018; Seijas et al., 2020) as well as three DSLs for the Ethereum chain, namely i) the unambiguous and composable derivative language *Findel* (Biryukov et al., 2017), ii) the visualization featured language *DasContract* (Skotnica et al., 2020; Skotnica and Pergl, 2020), and iii) a multi-level system that separates DSL-based smart contracts from their execution by Egelund-Müller et al. (2017). Arusoaie (2021) formalize the semantics of *Findel* and develop an infrastructure which tests a list of derived properties which—if fulfilled—exclude security vulnerabilities in *Findel*-based financial derivative contracts. Spiridonov (2021) sketch a theoretical concept for smart contract descriptions based on natural language constructions, leaving a practical testing for later publication.

Financial tokens in DeFi: Based on smart contracts, store of value forms with various functionalities and customization possibilities beyond native blockchain cryptocurrencies such as Ether were invented, summarized under the term 'tokens' (Chen et al., 2019a; Hu et al., 2019; van der Merwe, 2021). The 8 papers in this subcategory conceptualize financial token forms, analyze token characteristics (dominantly of stablecoins) or develop new token standards for DeFi applications.

A highly researched token class are stablecoins, invented to resolve cryptocurrencies' volatility issue—an issue which constitutes a major hindrance to cryptocurrencies' wide-scale adoption (van der Merwe, 2021; Pernice et al., 2019). Klages-Mundt et al. (2020) point out that stablecoins can and already have deviated from their peg and exhibited significant volatility. For non-custodial stablecoins—those adhering to DeFi principles[2]—they formulate risk models to measure incentive-based security and economic stability of stablecoin designs as well as outline how these models can be applied to DeFi applications. Pernice et al. (2019) analyze 24 permissionless stablecoin projects and derive a taxonomy based on stabilization techniques, monetary and exchange rate regimes, as well as the degree of decentralization. Moin et al. (2020), on the other hand, propose a taxonomy involving the peg, collateral, price stabilizing, and measurement mechanism used. Both papers point out weaknesses of trustless stablecoins, namely that i) those with digital collateral require well-designed mechanisms to handle volatility swings (Moin et al., 2020), ii) non-collateral-backed, algorithmic stablecoins rely on users' expectations and the issuing mechanism's reliability—which as seen in the case of the protocol *NuBits* might fail (Moin et al., 2020), and that iii) the proxy and self-collateralization rely on margin calls with questionable robustness (Pernice et al., 2019). Further, both agree that decentralized stablecoins depend

[2] Stablecoins can be designed custodial, i.e., utilizing third parties to store the underlying pegged asset of the stablecoin or non-custodial, i.e., implemented solely through smart contracts (Klages-Mundt et al., 2020).

on well-designed decentral off-chain data integration. A new design for cross-chain stablecoins based on modern risk management is presented by Liu et al. (2020).

New ERC token standards, on the other hand, are developed by Hu et al. (2019) and Davydov et al. (2019). Hu et al. (2019) propose an alternative to stablecoins to resolve the volatility issue of cryptocurrencies. The standard of their *ERC-1* token shifts the exchange risk from merchants and customers to the assumed less risk-averse cryptocurrency issuer. Davydov et al. (2019) propose a token standard (*ERC-T*) which combines characteristics of fungible ERC-20 and non-fungible ERC-721 tokens to enable the fractionalization of unique assets as digital security portfolios and hence ETF-like products in the crypto-asset world.

Matsuura (2019) develops a general token model and interpretation function to support the enablement of more stable finance applications and future academic token research—research which he suggests to be based on open transaction data and in the field of financial engineering.

DeFi decentralized applications (DApps): The with 18 papers largest subcategory are financial DApps**.** In this area, scholars analyze existing DeFi applications and also often invent own PoCs (9 papers). As in the Ethereum-dominant world of practical applications (Chen and Bellavitis, 2020), DApp research, with 13 papers, does heavily focus on the smart contract pioneer blockchain system.

As in traditional finance, excess assets can generate returns beyond underlying price movements by lending them to someone with shortage of that same asset. Two risks for crypto-asset lending involve the i) volatility-driven monetary instability and ii) counterparty risks between borrowers and lenders (Okoye and Clark, 2018). Hence, DeFi lending services work with overcollateralization requirements for the borrower. One discussed loan service category in the literature sample are P2P mechanisms: a system based on lenders' self-risk assessments of borrowers' collateral certificates (Yang et al., 2019), a P2P lending and bond issuance framework using collateral and insurance in the form of credit default swaps (Okoye and Clark), and a P2P collateral-based lending system with smart-contract-based credit scoring and underwriting mechanisms on loan history transaction records (Reno et al., 2021). An alternative to P2P lending are protocols, in which funds from lenders are pooled and interest rates are derived programmatically by supply and demand. In some sense, these protocols hence replace intermediaries' role of providing a market for loanable funds (Gudgeon et al., 2020b). While the so far discussed loan protocols enable short selling and leveraged long trading, the collateral impedes 'true' borrowing, i.e., entering a position of net debt (Gudgeon et al., 2020b)[3]. Moreover, locked collateral incurs opportunity costs, i.e., the inability to compile returns beyond price changes in the collateral itself (Harz et al., 2019; Kim, 2021). Hence, Harz et al. (2019) present *Balance*, an incentive-based, dynamic collateral design which they show can reduce overcollateralization by 10% while maintaining the same level of utility and security. Tien et al. (2020) implement a solution in which capital locked in smart contracts is supplied to the liquidity pools of *Compound*, providing an historical average annual percentage yield of 4%. Kim (2021), on the other hand, proposes a loan system in which borrowers can increase collateral utility by betting on price movements of their collateral position; yet acknowledging that the approach requires further research to cope with changed scenarios for forced liquidations.

While the so far discussed DApps serve as marketplaces for lenders and borrowers, so called 'Automated Market Makers (AMMs)' serve as an alternative means to increase the time value of money through deposits in fixed ratio 'asset pools' (Angeris and Chitra, 2020). As other parties can swap the deposited tokens of the respective pool (for a rate determined by the liquidity reserve), AMMs also function as DEXs. Moreover, using arbitrage theories, Angeris et al. (2019), Angeris and Chitra (2020), and Bartoletti et al. (2021) are able to show that AMM users are incentivized to perform actions which keep AMMs swap rates in line with actual exchange rates, giving AMMs a third property, namely that of price oracles (mechanisms to feed external data to the blockchain). While AMMs constitute one family of DEXs, the design space of alternative DEXs is large, comprising also order-book and both off-chain

[3] An exemption for net borrowing for the duration of one transaction ('flash loans') is discussed on the meso-level.

and on-chain trade execution mechanisms, all with their own characteristics (Tsai et al., 2020) as well as benefits and trade-offs (Lin et al., 2019).

Further DApp use cases presented are i) protocols to substitute stock exchanges (Pop et al., 2018; Sridhar et al., 2020) including a stock exchange solution based on smart contracts which are accessible by machine learning-based prediction models for stock market prices (Bansal et al., 2019), ii) decentralized auctioning of invoices (Guerar et al., 2020; Guerar et al., 2019), and iii) the proposition to create decentralized structured products (i.e., combinations of instruments such as bonds, stocks, and derivatives) to make this yet to professional investors restricted product class also available for retail investors (Grant et al., 2020).

3.3 Literature synthesis—Meso level

The meso-level is subcategorized by the research objective. In the with 17 papers larger subcategory '**DeFi single-chain ecosystem insights**', authors analyze empirical DeFi patterns and focus on the blockchain with the highest amount of transaction data, namely Ethereum (15 papers). The second category ('**Scaling beyond stand-alone DeFi ecosystems**'), entails research on how to interconnect blockchain systems for DeFi (e.g., Ethereum and Cardano) and integrate off-chain data (e.g., non-cryptoasset prices).[4] PoCs present the dominant research method with in total 9 out of 13 papers.

DeFi single-chain ecosystem insights: As traditional finance, DeFi suffers from financial scam constructs. A prominent scam copied to the smart contract world is the 'Ponzi scheme', i.e., 'high yield investment programs' in which investors' return stems only from the investments of further customers joining the scam (Bartoletti et al., 2020a; Lou et al., 2020; Bian et al., 2021; Chen et al., 2019b; Chen et al., 2021). By identifying and analyzing Ponzi schemes on Ethereum and employing a machine-learning based detection model, Chen et al. (2019b) estimate that before July 2017, around 500 smart Ponzi schemes were created, accounting for ~0,03% of all Ethereum contracts. Among the papers which develop detection models for Ponzi schemes on Ethereum, the highest F-Score (a measure of a model's accuracy) is reported by Chen et al. (2021). By utilizing a semantic-aware detection approach, the authors suggest a 100% F-score in experimental results, thereby outperforming reported F-Scores from detection tools by Chen et al. (2018), Jung et al. (2019), Lou et al. (2020), and Bian et al. (2021). To avoid Ponzi schemes, Bartoletti et al. (2020a) recommend investors to check the fund's advertisement for too alluring conditions and to analyze the contract code and transaction logs for scam patterns using, for example, the detection tools discussed above. Another financial scam is 'wash trading', in which a group of traders (or a single trader with multiple accounts), trade within their own cycles without eventually changing positions. They thereby manipulate the sentiment of tokens by high trading volumes (Victor and Weintraud, 2021). Analyzing the transactions of two Ethereum DEXs, the authors find that on both DEXs, 30% of tokens have already been wash-traded and that on one of them, 10% of tokens were exclusively subject to wash trading.

A second category of malicious DeFi activity are financial attacks. Daian et al. (2020) find that some of the surging arbitrage bots in DEXs bid up transaction fees to obtain priority ordering in transaction blocks. Further, the authors find that this mechanism, which they call 'priority gas auctions', poses a systemic risk to consensus-layer security and hence the Ethereum ecosystem, since those ordering optimization fees incentivize and enable so called 'miner-extractable-value (MEV)', i.e., value which miners can extract through manipulation of transactions. A phenomenon also assignable to MEV is 'front-running': through access to upcoming transactions, miners can extract privileged information about price slippages and place own transactions before or instead of others in the confirmation block (Struchkov et al., 2021). An extension of 'front-running' is the 'sandwich-attack', in which a miner places one order just before the victim transaction (i.e., front-run) and another one right after it (Zhou et al., 2021). Through transaction sequencing, cryptographic techniques, and appropriate DApp design,

[4] Here discussed papers focus on decentral, trustless finance applications but the related fields are larger and can for example be read up in the cross-chain interoperability survey by Belchior et al. or the oracle review by Al-Breiki et al. (2020).

front-running risks can yet be reduced (Eskandari et al., 2020). Another vulnerability on DEXs are 'fake deposits', for which Ji et al. (2020) develop *DEPOSafe*, a pattern-based tool to detect such vulnerabilities in ERC-20 smart contracts. A more holistic tool to detect DeFi attacks is *BlockEye*, pursuing end-to-end economic transactions analyses, thereby enabling the identification of whole sequences of malicious transactions and dependencies across DeFi projects (Wang et al., 2021a). As seen in the financial crisis, the failure of a single entity can have huge implications on the financial system as a whole—an interdependency risk which also exists in DeFi: assets created in one protocol (e.g., a stablecoin) are used as collateral or to earn interest in other DApps (Gudgeon et al., 2020a; Tien et al., 2020). If the assets fail, all connected protocols will be affected, potentially leading to a collapse as seen on March, 20th 2020 when the price drop of Ether led to the instability of the stablecoin DAI (Tien et al., 2020). By applying stress-testing mechanisms from traditional finance, Gudgeon et al. (2020a) simulate how a protocol liquidity dry-up could plausibly lead to an undercollateralized and hence insolvent DeFi lending system and a DeFi financial shock. Further, by testing two attack strategies, Gudgeon et al. (2020a) demonstrated the feasibility of attacking *Maker's* governance design, enabling the theft of $0.5bn of collateral within only two blocks. One of the two strategies employed so called 'flash loans'—a solely on blockchains existing method of uncollateralized borrowing under the condition that the borrowed assets are paid back within the same transaction (Wang et al., 2021b).

While the discussed research generates first empirical insights into DeFi activity using network-based 'detection', Wu et al. (2021, p. 18) claim that most studies so far on network 'profiling' (i.e., extracting descriptive information from networks) are not comprehensively discussing the implications of DeFi, which has "seriously affected the shape of the original cryptocurrency market as well as cryptocurrency transaction networks". One study characterizing transactions statistics of the high-scalability networks of EOSIO, Tezos and XRPL is conducted by Perez et al. (2020). The paper discusses the trade-off of low fees but many low-value spam transactions as in EOSIO and XRPL, or high transaction fees as in Ethereum—co-driven by a DeFi surge—yet in turn deterring a further usage spread. They suggest Tezos as suitable for DApps such as asset tokenization due to its well-defined smart contract semantics and EOSIO for DEXs with on-chain order placements due to the absence of fees and high throughput.

Scaling beyond stand-alone DeFi ecosystems: Operating across blockchain systems poses a complexity for DApps, such that CEXs remain the preferred tool for cross-chain transfers (Bentov et al., 2019; Zamyatin et al., 2019) while DeFi suffers from fragmentation (Borkowski et al., 2019; Han et al., 2019). Hence, scholars in this subcategory have developed prototypes for trustless cross-chain asset exchanges. One area are advancements of the 'atomic cross-chain swap', a solution first discussed by Herlihy (2018). Han et al. (2019), Wang et al. (2021c), and Rueegger and Machado (2020) show that the classic atomic swap is equivalent to a premium-free American call option for the swap issuer (given the optionality to abort the swap within a given time frame) and thus unfair for the participant. Hence, the former two papers design and implement swap solutions which estimate the premium value and price it fairly. Further advancements and (technical) alternatives to the atomic swap are presented in i) *XClaim*, a protocol using chain relays and cryptocurrency-backed digital assets to enable trustless cross-chain token issuance, transfer, redemption as well as cheaper and faster exchanges than atomic swaps (Zamyatin et al., 2019); ii) in *DeXTT*, built on top of existing blockchains allowing also for cross-chain one-way transfers by ensuring balance synchronization across the participating blockchains (Borkowski et al., 2019); iii) in *AgentChain*, where users map assets from other blockchains through decentralized trading groups' multi-signature deposit pools (Li et al., 2019); iv) *Xchain*, enabling cross-chain transactions even if they include sequenced and off-chain steps (Shadab et al., 2020); v) and by Lei et al. (2019), discussing a P2P cross-chain trading system with equilibrium pricing techniques. Alternative use cases to swaps and transactions are discussed by Tefagh et al. (2020), proposing the first cross-chain bond issuance protocol *Atomic Bonded Cross-chain Debt* (*ABCD)* and by Shekhawat et al. (2021), suggesting to transfer digital assets and DeFi operations to the cross-chain-interoperable blockchain Polkadot.

Miners verify computations on-chain but there is no built-in mechanism to verify 'real-world' data generated outside the blockchain (George and Lesaege, 2020; Park et al., 2021). So called 'oracles' import verified off-chain information on-chain and are thus a critical bridge for DeFi DApps to integrate data as pegged currency prices or events (Kumar et al., 2020; Park et al., 2021). One class of decentralized oracles are incentive-based voting schemes, e.g., by i) rewarding votes that are coherent with the majority of other votes and vice versa ('Schelling Point' mechanisms), ii) using reputation-based systems for data-feeding nodes as in *Chainlink*, or iii) the approach of *Maker DAO* in which token holders are incentivized to correctly report on the USD price to ensure stability of *Maker DAO's* USD-pegged stablecoin DAI (George and Lesaege, 2020; Park et al., 2021). Another group of oracles are presented by AMMs, discussed earlier—however, they are limited to price reporting of AMM-traded assets.[5]

3.4 Literature synthesis—Macro level

On the macro-level, authors apply a holistic perspective. 8 studies analyze characteristics of the DeFi ecosystem ('**Research on the DeFi space as a whole**') and 10 studies investigate DeFi's out-of-ecosystem impact, i.e., on the financially excluded population, on the legacy financial system, the subsequent need for regulation and likely long-term evolution ('**DeFi in the broader societal context**'). Most of the in total 18 papers apply a descriptive conceptualization approach (14 papers) and given the holistic perspective, most papers are blockchain system-independent (10 papers).

Research on the DeFi ecosystem as a whole: Authors in this field conceptualize the DeFi ecosystem either by pointing out its benefits and opportunities, deriving risks and challenges, extracting uses cases or by analyzing its agents (i.e., participants in the DeFi ecosystem). Starting with the benefits and opportunities, the most prominent advantages named besides disintermediation are the borderlessness (Chen and Bellavitis, 2020; Popescu, 2020), the openness fostering both trust (Chen and Bellavitis, 2020; Schär, 2021) but also innovation (Chen and Bellavitis, 2020), accessibility for anyone with a smartphone and internet connection (Schär, 2021; Zhang, 2021) as well as the absence of censorship opportunities (Popescu, 2020; Zhang, 2021). Some advantages are simultaneously evaluated as risks or limitations: First, whereas the composability of DeFi primitives is seen as an advantage for accelerated financial innovation (Chen and Bellavitis, 2020; Jensen et al., 2021; Popescu, 2020; Schär, 2021), it can also be viewed as an interdependency and systemic risk, given the high degree of contagion in case of application failures (Jensen et al., 2021). Second, while Schär (2021) argues that smart contract-based financial services increase efficiency, the Ethereum gas costs and network congestion are also posed as key challenges in DeFi (Chen and Bellavitis, 2020; Jensen et al., 2021). Third, DeFi enhances privacy in the sense that ownerships of wallet addresses are not disclosed (Schär, 2021); however, this may foster illicit activity (Schär, 2021) and on the other hand, privacy is also reduced as all transactions are stored on a public blockchain (Chen and Bellavitis, 2020). That regulatory uncertainty (Chen and Bellavitis, 2020; Popescu, 2020; Smith, 2021), illicit activities (Chen and Bellavitis, 2020; Schär, 2021; Smith, 2021), off-chain data integration (Chen and Bellavitis, 2020; Schär, 2021), governance and operational risks (Jensen et al., 2021; Schär, 2021), as well as the sole reliance on code integrity/ security (Chen and Bellavitis, 2020; Jensen et al., 2021; Schär, 2021; Smith, 2021) pose challenges and risks for DeFi, is agreed upon scholars in this field.

Synthesizing proposed use cases, Chen and Bellavitis (2020) name decentralized currencies, payment services, fundraising, and contracting as major DeFi business models. Schär (2021), Jensen et al. (2021), and Stepanova and Eriņš (2021) further specify the contracting category and analyze the use cases of DEXs and AMMs, lending platforms, derivatives, and automated on-chain asset management. While the use cases largely fit to the micro-level findings of this literature review, the latter two, i.e., derivatives and on-chain asset management, are less covered in our sample. Moreover, Schär (2021) proposes a DeFi stack, comprised of five layers: the i) settlement layer (relatable to the here discussed 'Financial smart contracts' subcategory), ii) asset layer (relatable to this review's 'Financial tokens in DeFi'), iii)

[5] While there exist further oracles, they are not fully decentral, as in the case of TLS-based schemes, which rely on trusted third-party TLS enabled website (George and Lesaege (2020)) or trusted hardware (Park et al. (2021); Zhang et al. (2016).

protocol layer (relatable to the proposed 'Financial DApps' bucket, iv) application, and the v) aggregation layer. While the first three layers are researched in further depth by papers in this review's sample, the application and aggregation layer are not yet specifically covered by other authors.

Two papers in our sample conduct research on DeFi agents. The paper by Jensen et al. (2021) conceptually categorizes DeFi agents into four groups: i) users, ii) liquidity providers, iii) arbitrageurs, and iv) application designers. The paper by Lockl and Stoetzer (2021) focuses on the first group, i.e., DeFi users: by gathering primary data among DeFi users, the authors test whether blockchain pioneers' driver, i.e., distrust in financial institutions, positively affects DeFi adoption—a relation they cannot confirm.

DeFi in the broader societal context: Referring to the work of Yaga et al. (2018), Abdulhakeem and Hu (2021) suggest that blockchain is the technology to likely impact our lives the most for the next decades. One discussed impact is the financial inclusion of the unbanked population—representing ~bn 1.7 people as of 2017 (Abdulhakeem and Hu, 2021; Demirgüç-Kunt et al., 2020). To support successful financial inclusion solutions, Larios-Hernández (2017) analyzes habit-based sensitives towards financial services of the unbanked and conclude that 'semi-formal'-services (i.e., in the middle ground of full decentralization and incumbents' financial services) are most prone to succeed. Clippinger (2016) and Duran and Griffin (2021) study DeFi's impact on legacy financial intermediaries. Clippinger (2016) finds that the digital disruption in the newspaper industry holds analogies with the threat of smart contract enabled services on banking. As a survival strategy he suggests banks to authentically work on behalf of customers' interests and names lack of trust in institutions' proper personal data management as an important challenge to solve. This yet contradicts Lockl and Stoetzer (2021) who do not confirm a positive relation between distrust in financial institutions and DeFi adoption. Duran and Griffin (2021), on the other hand, find that similar factors contributing to the financial crisis, can also be found in the automated and interconnected smart contract world, potentially impacting the stability of the global financial system. By pressing for technical improvements, better monitoring, and robust standards, they suggest regulatory bodies could reduce these risks, yet claiming that if smart contracts are used in high volumes to hold funds in escrow and facilitate transfers, it may be better to require certain settlement types via central counterparties or consortiums instead of following a fully decentralized approach**.**

That DeFi regulation is important, is agreed upon scholars (e.g., Ellul et al. (2020), Paech (2017), Larios-Hernández (2017), Duran and Griffin (2021)). However, regulating DeFi is non-trivial, mainly driven by i) the difficulty of determining the applicable jurisdiction and law in a borderless market (Zetzsche et al., 2020), ii) lack of enforcement power in the absence of clear accountabilities (Zetzsche et al., 2020), and iii) censorship resistance, i.e., preventing third parties to confiscate assets (Johnson, 2021). Guseva (2020) analyzes empirical data in the US and finds that the SEC's flexible enforcement approach is not suitable anymore after the SEC's inconsistent game-theoretic behavior in three recent legislation cases, leading to increased uncertainty of market participants. With DeFi protocols issuing governance tokens, she suggests aiming for more formal regulation. Evaluating the ecosystem from a tech side, Ellul et al. (2020) point out that jurisdictions have so far mainly focused on financial aspects as cryptocurrency usage and have put insufficient focus on regulating the technological risks stemming from blockchains and smart contracts, hence proposing a technology assurance regulatory environment. A related thought is taken by Zetzsche et al. (2020), proposing an 'embedded regulation' for DeFi, meaning that regulatory requirements are to be integrated in the technological structures which enable DeFi in the first place. The integration could be enforced through an external guarantor, i.e., a "platform where the regulation is embedded and that facilitates supervisory cooperation" (Zetzsche et al., 2020, p. 202). However, the authors argue that while this would enable effective oversight and risk control, it would require a small part of the value chain to become reconcentrated—a state which they claim to be inevitable.

Overall, a common theme emerges in DeFi studies in the broader societal context: the questionability of large-scale enforceability of a fully decentralized financial system. Paech (2017) provide further support, arguing that finance will largely continue to rely on an intermediary-client approach, e.g., as individual clients are subject to private and thus local law irrespective of alternative code-based network rules.

Hütten (2019) adds another angle and points out that the DeFi space itself becomes less decentralized as blockchain utopians' commitment to strictly adhere to code-based governance has crumbled after the failure of the DeFi protocol *The DAO*. Further, Hütten (2019) poses that the very institutions that blockchain pioneers meant to replace, embrace the technology for their own operations, leading to an evolution of financial capitalism rather than a revolution. Similarly, Paech (2017) predicts that the expected revolution will primarily introduce new technologies enabling the current financial market model to become more efficient, and Abdulhakeem and Hu (2021) propose that blockchain technology does not necessarily need to overthrow the incumbent system but rather complement it.

4 Fields for further research

To derive fields for further research, we applied three angles to our literature synthesis. First, within our framework's subcategories, we identified understudied areas or those with non-conclusive findings as in the case of DeFi network profiling studies or DeFi regulation research. Second, across our framework, we searched for inconsistencies among papers as in the case of authors pointing out the importance of oracles or the existence of an aggregation layer and on-chain asset management, but with few or no relatable research in our sample. Third, we added the angle of research methodologies and blockchain focuses applied and derived areas with room for more academic efforts. While, in the accelerating DeFi space, we expect further research in all discussed framework buckets, our analysis suggests four research directions which will best support the further advancement of the DeFi space:

Research on DeFi protocol interaction and aggregation layers: Whereas the DeFi framework of Schär (2020) states that on top of DeFi protocols there are other layers of user-friendly DeFi service applications and aggregation DApps (and real-world protocols as *YearnFinance* show those aggregation platforms indeed exist), we did not find respective peer-reviewed research. The same reasoning applies to on-chain derivatives and asset management research—use cases in which scholars could prove the praised potential of DeFi composability. We propose to utilize openly accessible transaction records (secondary data) to provide insights on i) how different DeFi DApps empirically interact, ii) find yield farming patterns across and beyond the here discussed lending and liquidity pool rewards (e.g., also involving staking), iii) as well as empirically analyze the associated role of aggregation protocols.

Decentralized oracle applications and their integration to DeFi DApps: Scholars agree that off-chain data integration poses a challenge for DeFi: Chen and Bellavitis (2020) derive that the inability to objectively codify off-chain data on the blockchain, may limit the efficiency and usefulness of a decentralized system of distributed trust. Further, Schär (2021) points out that the dependency on oracles for off-chain data integration introduces dependencies and implies risks of centralized contract execution. Schär (2021) suggests that these risks may be mitigated by decentralized oracles, however, scientific research on fully decentralized oracle designs for DeFi DApps is yet scarce. Some oracle designs discussed in the DeFi context are not fully decentral, as in the case of TLS-based schemes which rely on trusted third-party TLS enabled websites (George and Lesaege, 2020) or trusted hardware (Zhang et al., 2016; Park et al., 2021). To enable more use case opportunities involving off-chain data, we therefore suggest further proof-of-concept research on decentralized oracle integration to DeFi DApps.

Agents/ participants in the DeFi ecosystem: So far, only little light has been shed on DeFi ecosystem participants. In our literature sample, Jensen et al. (2021) conceptually divide DeFi agents into users, liquidity providers, arbitrageurs, and application designers, whereas papers as for example by Angeris and Chitra (2020) and Harz et al. (2019) model incentive-based behavior of different agents on specific DApp categories as AMMs, DEXs or liquidity pools. We suggest further research in this area, especially by conducting primary and secondary data studies. A related study using primary data can be found by Tana et al. (2019), conducting an ethnographic study among miners, traders, and developers. However, in their resulting typology of agents, namely 'Novice' (54%), 'Fortune Hunter' (21%), 'Knowledge-Seeker' (17%), and 'Visionary' (6%), they only discuss the latter in conjunction with DeFi. For secondary data studies, Wu et al. (2021) point out that most papers extracting descriptive information from cryptocurrency networks, are not comprehensively enough discussing the implications of the emergence of DeFi. One study that can be related to this claim and which can be used as a springboard for DeFi-specific studies is the one by Liu et al. (2021), analyzing Ethereum token transactions—i.e., excluding ether transfers and (highly DeFi relevant) smart contract calls—to identify economic agents. Gaining a better view on DeFi agents will improve our understanding of the ecosystem's dynamics, adaptors' motivations (which as shown by Lockl and Stoetzer (2021) is not solely driven by distrust in intermediaries), and enable a targeted derivation of key levers to further advance this still emerging ecosystem.

Regulation of DeFi: Research non-conclusively answers how DeFi can effectively be regulated. The book chapter contribution by Maia (2021) suggests that while the European proposal for a 'Regulation on Markets in Crypto-assets (MiCA)' is a first step to regulating non-trustless crypto-asset markets, the regulation does not address the early-state DeFi trend. For upcoming legislation, Maia (2021) suggests that besides establishing incentives for self-regulatory contributions, authorities should integrate efforts with private bodies to establish public entities which, e.g., through governance tokens, can actively participate in DeFi-protocols and monitor and steer the protocol's risks as well as report systematic risks to authorities. However, the exact design is still unspecified. As long as DeFi operates under regulatory uncertainty, many entrepreneurs, developers, investors, and users will refrain from entering the space. Finding supra-regional solutions for the borderless DeFi space makes the challenge even more complex and requires academic support. As so many stakeholders are involved, we propose this field as a good area for primary data research—of which only one study exists so far.

5 Discussion and concluding remarks

Our review offers five distinct contributions. First, we show that the number of DeFi publications is rising with 55 out of 83 articles only published in 2020 and the first half of 2021. 50 out of the 83 papers were published via conferences, which is an expected dynamic in rapidly evolving information system research fields. Second, we present a framework structuring DeFi research into three levels of perspective: i) the micro-level with research around individual DeFi components, namely financial smart contracts, tokens, and DApps, ii) the meso-level with research on characteristics within as well as on scaling solutions beyond single-chain systems, and iii) the holistic-perspective macro-level, conceptualizing the DeFi space as a whole as well as its societal implications and need for regulation. Third, in line with applications in practical use, academia has focused on the Ethereum blockchain so far with 49 out of 83 papers. Fourth, we find that prototyping/ PoCs are the dominating research methodology whereas openly available, secondary transaction data is so far merely used for fraud detection studies and only one paper has used primary data. Finally, we identify four research avenues to further advance the DeFi space, namely i) research on DeFi protocol interaction and aggregation DApps, ii) improvements of decentralized oracles and their integration to DeFi DApps, iii) analyses on participants of the DeFi ecosystem, and iv) practical suggestions for effective DeFi regulation.

We thereby provide the first systematic overview of academic DeFi literature to date and derive research avenues in this yet fragmented scientific field. There are two limitations which we want to point out. First, like other systematic reviews, our paper may suffer from biases, e.g., in sample selection and data interpretation. Second, we needed to ensure a manageable number of papers. Therefore, we excluded i) adjacent, interdependent research such as on non-finance specific smart contract, decentralized governance, and blockchain-related studies as well as ii) DeFi book publications and recent DeFi-related legislations. An inclusion of those sources would extent the comprehension of this review even further and is thus suggested for further reviews in this field.

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