



# Standardization in the context of transdisciplinarity

Knut Blind<sup>1</sup> 

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## Abstract

Transdisciplinarity is an integrative approach that includes different scientific disciplines as well as stakeholders and researchers to tackle both societal and scientific challenges. Since standards are jointly developed by science, business, and other stakeholders, standardization can be perceived as a specific mode of transdisciplinarity. In the discussion on knowledge transfer as a further performance dimension for researchers, participation in standardization procedures is now also being considered as a further channel, albeit without a sound conceptual and empirical basis. The paper thus aims to provide a conceptual base of standardization as a transdisciplinary knowledge production mode and transfer channel but also gives an outlook on its empirical implementation. The literature review on transdisciplinarity helps us to put standardization into the context of transdisciplinary research and to present a conceptual model of standardization as transdisciplinary knowledge production and transfer. Further, we present the first methodological approaches for the empirical analysis of the transdisciplinary character of standardization. Finally, we conclude with a summary, a number of recommendations derived from transdisciplinary research for standardization, and an outlook toward future research to be tackled with the proposed methodologies.

**Keywords** Standardization · Transdisciplinarity · Knowledge production · Knowledge transfer

## Introduction

Transdisciplinarity has a long history as a research approach (see, for example, the overview in Lawrence et al. 2022). It is increasingly promoted as an adequate scientific response to pressing societal problems (OECD 2020), like climate change, because it requires new knowledge production and decision-making methods (Renn 2021). In particular, the involvement of non-academic actors in the research process has been highlighted in the context of transdisciplinarity to integrate all relevant knowledge, consider a broad spectrum of views, and create ownership of real-world problems and possible solutions. For over a decade, broadly accepted definitions of transdisciplinarity have been available (e.g., Jahn et al. 2012; Lang et al. 2012). In parallel, transdisciplinarity has become an established position in research, which is

confirmed by the increasing number of peer-reviewed publications and the citations they have received to date. However, the methods applied in transdisciplinary research are challenged with regard to their quality (Lang et al. 2012) and are dominated by case studies (Brandt et al. 2013; OECD 2020).

Only recently has standardization been considered an effective channel of knowledge transfer. This reorientation is reflected in the new transfer initiative within the framework of Germany's Federal Government's High-Tech Strategy,<sup>1</sup> including the new Zukunftsstrategie,<sup>2</sup> and in the new taxonomy of transfer indicators of the Joint Science Conference (Gemeinsame Wissenschaftskonferenz—GWK), which included standardization as a seventh pillar (GWK 2021). The European Commission has also explicitly accepted standardization as a transfer channel in the past Horizon 2020 and the current Horizon Europe

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Handled by Christian Pohl, Eidgenössische Technische Hochschule Zurich, Switzerland.

✉ Knut Blind  
knut.blind@isi.fraunhofer.de

<sup>1</sup> Fraunhofer ISI & TU Berlin, Sekr. H47, Straße des 17. Juni 135, 10623 Berlin, Germany

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<sup>2</sup> [https://www.bmbf.de/bmbf/de/forschung/zukunftsstrategie/zukunftsstrategie\\_node.html](https://www.bmbf.de/bmbf/de/forschung/zukunftsstrategie/zukunftsstrategie_node.html)

research framework program. Recently, a Code of Practice on standardization was published to guide researchers and research organizations (European Commission 2023) contributing to the implementation of the EU strategy on Standardization (European Commission 2022). With a slight delay, the Biden-Harris Administration (2023) published the United States Government National Standards Strategy, pointing to the role of research and development results as a base for future standards for critical and emerging technology. At the international level, standardization has now found consideration in OECD publications on the commercialization of R&D results (OECD 2013), in the Oslo Manual on Innovation Measurement (OECD 2018), and, recently, as an essential pillar of innovation systems (OECD 2022).

However, standardization is not only an effective channel of knowledge transfer aimed at solving matching problems (De Vries 1997) but can also be considered a mode of knowledge production in general (e.g., Bar and Leiponen 2014; Baron et al. 2016) and addressing sustainability challenges in particular (Blind and Heß 2023). Due to the involvement of actors from industry, academia, and research, as well as representatives of societal interest groups and governmental organizations, standardization has, at least in this dimension, some similarities to transdisciplinary research, although with a different composition of contributors. However, further commonalities need to be identified.

Therefore, the first aim of this paper is to find common ground between standardization and transdisciplinarity. Based on an analysis of current scientific literature, we first identify the main features of an emerging framework of transdisciplinarity as applied to standardization. Second, building upon this framework, we present a conceptual model of standardization, following those of transdisciplinarity (Jahn et al. 2012; Lang et al. 2012). Third, we discuss methodological approaches applied in standardization research to tackle the aforementioned methodological challenges—if applicable—in transdisciplinary research.

The embedding of standardization in the context of transdisciplinarity has not yet been explicitly addressed. The integration and further elaboration of scientific insights into standardization in the context of transdisciplinarity are analyzed conceptually and empirically for the first time in this paper. Standards are usually drawn up by consensus of the so-called interested parties, including representatives from scientific organizations, and adopted by state-recognized organizations such as the International Organisation for Standardization ISO or its German member, the German Institute for Standardization DIN. If a company implements its standards, this indicates knowledge transfer in the sense of a concrete implementation of scientific and technological

knowledge in practice. If scientific publications are referenced in standards, then they are relevant for their implementation (Blind and Fenton 2022), i.e., the scientific knowledge generated is thus anchored in a standard. In the past, the importance of standards as a channel of interactive knowledge and technology transfer has been largely neglected. In recent discussions on mapping transfer as a performance component of science, participation in standardization processes is also being discussed and called for (European Commission 2023), but without a fundamental empirical basis. In 2020, Germany's Joint Science Conference (Gemeinsame Wissenschaftskonferenz—GWK 2021, p. 185) also included standardization as a further pillar in its transfer indicators. So far, only publications, patents, or spin-offs are considered in the core set of performance indicators. Despite their high importance for science and technology, standards have not been mentioned in previous position papers of the German Council of Science and Humanities (see Wissenschaftsrat 2016a, b). With the emphasis on the application orientation of research (see the current position paper of the German Council of Science and Humanities Wissenschaftsrat 2020), the importance of the channel from scientific publications to standards as proof of a successful knowledge transfer by researchers and their institutions might increase in the coming years. By considering standardization as a specific mode of transdisciplinarity, the above-mentioned initiatives focusing on transdisciplinarity can also help to further promote standardization.

Specifically, the following questions are addressed from the perspective of standardization as a mode of transdisciplinary knowledge production and transfer:

- What are the differences and similarities between transdisciplinary research and standardization?
- Which existing conceptual models of transdisciplinary can be applied to standardization?
- Which methodological opportunities exist related to standardization for addressing transdisciplinary research questions?

The remainder of the paper is structured as follows. The first chapter reviews the vast literature on transdisciplinarity relevant to our research questions. Then, standardization is put into the context of transdisciplinary research. The third chapter presents and elaborates on the conceptual model of standardization as transdisciplinary knowledge production and transfer. Next, we present the first methodological approaches for analyzing the empirical evidence about the transdisciplinary character of our conceptual model. Finally, the paper concludes with a summary, the challenges for empirical research, and an outlook toward future research.

## Literature review

Standardization and standards have been investigated in the last decades, particularly with regard to their economic impacts, e.g., on growth (ISO 2021) and trade (Swann 2010a, b). In addition to the important role of securing interoperability and reducing transaction costs by harmonizing company- or country-specific requirements, standards as knowledge pools are stressed. These insights on the macroeconomic level are complemented by evidence at the organizational and individual levels. In general, approaches are needed that reflect the implementation of knowledge in innovative products and processes, but also in society at large. After the Sustainable Development Goals' (SDGs) publication in 2016, endorsed by the UN General Assembly, the International Organisation for Standardization ISO started to attribute its standards to the SDGs based on the assumption that solid support from a broad portfolio of stakeholders is needed to achieve them.<sup>3</sup> Based on a survey of more than 1000 experts involved in standardization, Blind and Heß (2023) reveal which SDGs might benefit most from standards in general. However, this research is still in its early stages.

In contrast to the long tradition of analyzing patents applied by research organizations and universities, standardization has only recently been considered in the scientific work on knowledge transfer (see, for example, in the review article by Perkmann et al. 2021 compared to Perkmann et al. 2013). Insights into the involvement of companies (Blind and Mangelsdorf 2016; Blind et al. 2022a, b; Leiponen 2008; Rammer et al. 2016; Wakke et al. 2015) or research institutions (Blind and Gauch 2009; Zi and Blind 2015; Blind et al. 2018) in standardization are available. They reveal that firms join standardization processes because of knowledge seeking but also because they are searching for common solutions to technical and even societal problems (Blind and Mangelsdorf 2016; Blind et al. 2022c). Even at the individual level of engineers (Blind et al. 2022a), participation in standard-setting processes is a vital knowledge pool for their work, but also a mode to solve specific problems (Blind and Gauch 2009; Blind et al. 2018).

However, neither the role of interdisciplinarity nor that of transdisciplinarity in relation to both standardization and standards has been explicitly mentioned. The relevance of interdisciplinarity has only been indirectly proven by the important role of standardization in structuring converging technologies (Gauch and Blind 2015). However, related to transdisciplinarity, researchers highlight that they meet companies, still the dominating stakeholders in standardization

(e.g., Blind and Heß 2023 revealing quantitative evidence in Germany's standards institute DIN, and Balzarova and Castka 2012 analyzing their strong influence in the development of ISO 26000), in the work of technical committees, which creates opportunities for further joint research (e.g., Blind and Gauch 2009).

Complementary to the insights about researchers' involvement—both from companies and research institutes—collected via interviews and surveys, the more than 2 decade-long traditions of analyzing standard-essential patents (SEPs) reveal that these are declared both by companies and research organizations (Bekkers et al. 2023; Buggenhagen and Blind 2022). Therefore, companies and research institutes alike contribute knowledge to the joint development of standards. Whereas SEPs are focused on mobile communication technologies, the scientific publications referenced, e.g., in international standards, cover a broader range of disciplines (Blind and Fenton 2022). Still, they are mainly co-authored by researchers working for universities or other research organizations. However, five times more authors are employed by firms than by scientific publications from industry (Hermann et al. 2020). Obviously, standards development is also based on scientific inputs from research organizations and industry and is not solely driven by the demand of customers or even regulators (e.g., Moon and Lee 2022).

Standards are not only a knowledge transfer channel (Blind and Gauch 2009) or a further option for researchers' engagement in commercializing their research results (Perkmann et al. 2021). Since standardization processes integrate knowledge both from researchers and the industry, which will eventually implement them, they can be placed in the context of transdisciplinarity.

Indeed, standardization can also be linked to transdisciplinarity as an integrative approach by including different scientific disciplines and non-scientific stakeholders besides the researchers themselves (Tress et al. 2005, cited in Mauser et al. 2013). In concrete terms, the conceptual model of Jahn et al. (2012, p. 8) defines transdisciplinarity as:

Transdisciplinarity is a critical and self-reflexive research approach that relates societal with scientific problems; it produces new knowledge by integrating different scientific and extra-scientific insights; it aims to contribute to both societal and scientific progress; integration is the cognitive operation of establishing a novel, hitherto non-existent connection between the distinct epistemic, social–organizational, and communicative entities that make up the given problem context.

At the same time, Lang et al. (2012, pp. 2–3) provided a rather similar definition, which sees the scope of transdisciplinarity in “aiming at the solution or transition of societal

<sup>3</sup> Ikram et al. (2021) focus on specific international standards and elaborate in detail how they might contribute to the SDGs.

problems” or “complex societal and ‘wicked’ problems” (Kaiser and Gluckman 2023). Meanwhile, the approach of Jahn et al. (2012) has been expanded and revised, e.g., by Hoffmann et al. (2019), who, after defining sustainability problems, explicitly add the production and evaluation of new knowledge before the dissemination and use of new knowledge in science and practice as further steps.

Complementary to further differentiation of process steps, Pohl et al. (2021) try conceptualizing integration as a multidimensional interactive process. Eventually, they characterize it as an “open-ended learning process without pre-determined outcomes” linking previously unrelated participants having different cognitive and institutional framings. However, they also point out that not all participants have to be involved and that it can be one-sided and not mutual. The objects of integration can be concepts, frameworks, practices, and further insights. Consensus could, but has not been achieved within interdisciplinary research, because the plurality between the stakeholders could remain. However, the diversity of perspectives must be continuously considered during the process. In addition, not only do the different cognitive dimensions matter, but also do the individual characteristics and social interactions. Karrasch et al. (2022) take a closer look, not at the different stakeholders, but at the various types of knowledge, i.e., system, target, and transformative knowledge already introduced by Pohl and Hirsch Hadorn (2007), and further elaborated on, e.g., by Brandt et al. (2013), to be integrated within transdisciplinary research. Recently, Lawrence et al. (2022) presented a similar taxonomy complemented by process knowledge. As a further distinction, Brandt et al. (2013) look at researchers and non-academic actors. Their analysis allows them to identify barriers and factors for successful transdisciplinary research.

Standardization and standards can fulfill the requirements of transdisciplinary research claimed by Pohl et al. (2021), i.e., to tackle the complexity of the issues at stake, to consider practitioners’ and researchers’ diverging perceptions, to connect abstract and case-specific knowledge, and eventually to generate descriptive, normative, and transformative knowledge for sustainable development. Therefore, in the following section, we will compare standardization and transdisciplinary research to reveal similarities as well as differences. The final assessment will then allow us to show that it is possible to put the former in the broader context of the latter.

First, standardization processes, similar to transdisciplinary research (e.g., Lawrence et al. 2022), have the objective to address mainly economic, but also scientific and societal challenges (see, for example, the role of standards for addressing the SDGs by Blind and Heß 2023). The topics addressed both in transdisciplinary research and standardization are characterized by a high level of complexity. Current

examples are the initiatives to develop standards to establish the Circular Economy (Flynn and Hacking 2019) or smart cities (Jakobs 2024). In general, standardization addresses fields of converging technologies, which was quantitatively confirmed by the analysis of Gauch and Blind (2015).

Furthermore, standardization projects can be considered to be organized similarly to research projects, following specific objectives or terms of reference along a timeline structured by milestones and deliverables. However, standardization processes, at least in accredited national, European, or international bodies, have to follow the World Trade Organization’s principles of openness, whereas traditional research projects are usually closed. In contrast, transdisciplinary research is characterized by its openness to all relevant stakeholders (e.g., Kaiser and Gluckman 2023). In addition, the paradigm shift from closed to open innovation (Chesbrough 2003) allows or even encourages more interested participants or even a greater crowd to join research, particularly innovation projects. For software development, open source, characterized by an even higher degree of openness, is the dominant paradigm. It is mentioned, because it also has some similarities and interfaces to standardization (e.g., Boehm and Eisape 2021).

Looking at the stakeholders, researchers are certainly the dominant group in traditional and transdisciplinary research activities. However, other relevant stakeholders representing different groups in society, including actors from public administration as well as industry representatives, are also involved. In contrast, standardization processes are driven by the same groups but dominated by industry representatives (Blind and Heß 2023) and delegates from societal groups, researchers, and stakeholders from governmental organizations. Whereas the selection of participants in transdisciplinary research is driven by their ability to contribute to closing scientific and societal knowledge gaps, in standardization, the process follows other priorities. In general, industry starts standardization processes to solve technological or economic problems. However, other stakeholders, like environmental groups, might also call for a new standardization activity to protect environmental interests. Researchers are involved when, from the very beginning or later, the working group realizes that insights from researchers are needed to solve scientific or technical problems revealed before or during the standardization process.

With regard to the processes, Jahn et al. (2022) show five modes within transdisciplinary research along the three dimensions of orientation toward real-world problems, the intensity of interactions with non-academic actors, including citizens (Kaiser and Gluckman 2023), and the concrete contributions of the non-academic actors involved. In addition to purely academic research, they find practice consultation (see already Mobjörk 2010 on consulting transdisciplinarity), selective practitioner involvement, ideal-typical

transdisciplinary research characterized by a high level of knowledge integration defined as participatory transdisciplinarity by Mobjörk (2010), and rather practice-oriented research. Except for the relatively rare purely academic activities within transdisciplinary research, all other modes can be found within standardization processes, particularly those with a strong orientation toward real-world problems and a high intensity of interactions with and of contributions by actors outside of academia. Consequently, standardization can be considered as a specific mode within transdisciplinary research.<sup>4</sup>

Whereas transdisciplinarity as a research mode emphasizes the significance of approaches to efficiently achieve the integration of different types of knowledge, systems, targets, and transformation as introduced by Pohl and Hirsch Hadorn (2007) and empirically investigated, e.g., by Jacobi et al. (2022), there is little conceptual and empirical research conducted related to standardization processes.<sup>5</sup> One example is the case study about smart city standardization by Jakobs (2024). He first identified more than ten stakeholder groups, their roles and tasks, and their expertise relevant to the standardization process and the implementation of the developed standards. Whereas system and target knowledge are needed for the standardization process, transformation knowledge is required to implement standards effectively. However, Jakobs (2024) concludes with a proposal on how the different stakeholders and their expertise can be better integrated into future standardization processes. Not all of them are adequately and efficiently integrated, revealing shortcomings compared to sophisticated transdisciplinary research processes.

As mentioned above, integrating different types of knowledge (Brandt et al. 2013 or Lawrence et al. 2022) is key not only for the success of transdisciplinary research but also for standardization. Whereas consensus among the various stakeholders is a preferred but not the only option within transdisciplinary research, most standard-setting organizations (SDOs) highlight the importance of a consensus-finding process to eventually get to the publication of a standard. However, for most standardization bodies, consensus does not necessarily mean unanimity; only that no important

stakeholder group disagrees with the proposed standard (see Baron and Spulber 2018 for an overview).

Finally, the output of transdisciplinary research is artifacts that contribute to stocks and flows of knowledge (Pohl et al. 2021), i.e., academic output, such as scientific publications. However, Jahn et al. (2022) claim that transdisciplinary research gains less scientific outputs and impacts as commonly measured by the number of scientific publications and their respective citations and reveal that more practitioner interaction generates more societal outputs. Marg and Theiler (2023) elaborate on this topic, explaining it with the time-consuming transdisciplinary research process and the focus on societal effects. Obviously, there is a trade-off to master between the different outputs (see also Newig et al. 2019 or Jahn et al. 2022), i.e., projects have to decide whether they aim to be scientifically or societally successful (Marg and Theiler 2023). However, Lemaitre and Le Roux (2021) find no negative correlation. According to Renn (2021), this tension might ease, because the boundary between basic and applied research disappears within transdisciplinary research. Standardization processes eventually produce standards that can have a more scientific character, e.g., as measurement and testing standards, but are primarily intended to codify good practice, but are not necessarily state of the art in science and technology.

Closely related to the type of output of transdisciplinary research is its impact, i.e., more academic results generate impact in the academic sphere, whereas societal outputs have the potential to have an impact on society. However, Jacobi et al. (2022) reveal that only a small share of scientific knowledge generated within transdisciplinary research has so far resulted in changes in policy and practice. In contrast, standards primarily intend to impact the companies implementing them, e.g., securing interoperability of different components or promoting their productivity. Nevertheless, some standards, e.g., on terminologies, can contribute to progress in science and research (Blind and Gauch 2009) and are an important knowledge source for innovators (Großmann et al. 2016). However, there is particularly strong empirical evidence for the implementation of international standards, which form the basis for certification schemes, while it is lacking for the vast majority of standards (Blind et al. 2023). In addition, both the results from transdisciplinary research and the specifications defined in standards can provide evidence for public policies in general and regulation in particular (e.g., Gottinger et al. 2023).

The comparison between transdisciplinary research and standardization along several dimensions reveals that the latter can be understood as a specific category of the former, much broader concept. Consequently, we go one step further in the next chapter and present a modified conceptual model of transdisciplinary research adapted to standardization.

<sup>4</sup> In addition, there is a strong trend toward closer integration between research and standardization (see already Blind and Gauch 2009) recently mentioned in EU Strategy on Standardisation (European Commission 2022) and further specified by the Code of Practice on standardization by the European Commission (2023). However, even the United States published a national standards strategy (Biden-Harris Administration 2023).

<sup>5</sup> Furthermore, transdisciplinary research not only integrates but also produces knowledge, which can be an input for standardization processes, which themselves can generate additional knowledge based on the knowledge types mentioned above. We thank an anonymous author for pointing to this link.

## Conceptual model

The review of the literature on knowledge transfer via standardization and standards is the starting point, which focuses on the dimension of transdisciplinarity. The potential similarities with standardization were then examined along several dimensions. From the review of the literature and the comparison between transdisciplinary research and standardization, we have selected a conceptual model for transdisciplinarity and adapted it to standardization. Eventually, we decided to use the conceptual model of transdisciplinarity presented by Jahn et al. (2012), which was further developed by Hoffmann et al. (2019) and Pohl et al. (2021). There are two major reasons for this selection. First, Jahn et al. (2012) are after Lang et al. (2012), who have presented a rather similar approach going back to a previous paper by John (2008), but focus on sustainability science, the most cited paper on transdisciplinarity ahead of Mauser et al. (2013). However, the reason for not adopting the framework for interdisciplinary and transdisciplinary co-creation of the knowledge castle by Mauser et al. (2013) is its insufficient consideration of recursive knowledge flows and the missing differentiation between the realm of science and practice.

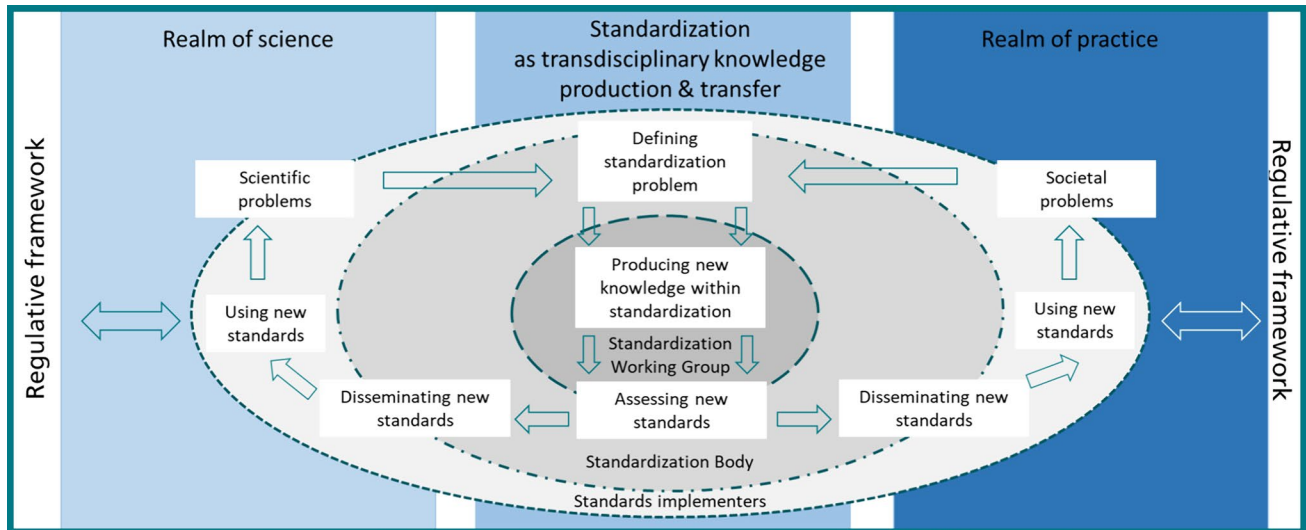
The model by Jahn et al. (2012) is based on the proposition that generating solutions for societal challenges requires connecting them to gaps in the current body of knowledge, i.e., scientific challenges. Consequently, transdisciplinary research contributes to societal and scientific progress to different degrees depending on whether more practical or scientific solutions are required.

There are three phases in the transdisciplinary research model by Jahn et al. (2012). In the first phase, the societal and scientific challenges are combined within a problem transformation process into a joint research object. This is essential to promote the cohesion and commitment of all parties involved through the whole transdisciplinary research process. In the second phase, new knowledge is produced through the contributions of researchers and other stakeholders via interdisciplinary integration. In the third phase, the results of the transdisciplinary process are assessed based on the societal and scientific contributions of all participants. This review round might help to improve the initial results. Finally, the generated knowledge is fed back by the involved scientists to the scientific and other participating stakeholders into the societal discourses, which may be the starting point of a new transdisciplinary research process. Following the—compared to Pohl et al. (2021)—more differentiated approach of Hoffmann et al. (2019), which revised the conceptual model presented by Jahn et al. (2012), we present standardization as transdisciplinary knowledge production and transfer.

In the first step, the problems, which are increasingly positioned under the SDGs (see Blind and Heß 2023), are defined within the standardization bodies. Then, working groups within a standardization body are formed involving actors from the realms of science and practice, depending on the main driving force beyond the standardization problem (Moon and Lee 2022). In this phase, the standardization process is anchored in both realms but by different weights depending, again, on the origin of the driving forces. Then, depending on the institutional setting and the governance of the standardization body, the level of informal and formal interactions between the stakeholders from both realms, at least throughout the process of knowledge production with the standardization process, is determined. Here, developing a joint vision for integrating different types and sources of scientific and practical knowledge contributed by a wide variety of stakeholders is helpful (Swann 2010a, b) and even required for the European standardization bodies according to Regulation (EU) No 1025/2012, also known as the Standardization Regulation. Furthermore, an outcome or impact model that specifies expected scientific and societal outcomes or impacts of the forthcoming standards and proposes key performance indicators would be appropriate but has so far not been established (see the recent approach by Wiegmann et al. 2023), developed for assessing ex post social impacts of standards). Previously, a technology road-mapping-based framework for the development of standards for emerging technologies was presented by Featherston et al. (2016) but not broadly implemented in practice.

In the second step, existing knowledge from science and practice is integrated into the standardization process. However, new knowledge is even generated within the process itself. Here, the challenge is to integrate different types of knowledge, e.g., from the scientific realm and practice. For example, the most recent insights from research might clash with the requirements raised by the practitioners in the industry (see Blind and Gauch 2009 or Blind and Fenton 2022). As Karrasch et al. (2022) claim for knowledge integration in transdisciplinary research, the juxtaposition of knowledge requires solving conflicts between contradictory subjective knowledge claims of different actors, which eventually also leads to the joint production of new knowledge.

In the third stage, the drafts of the new standards, potentially including new pieces of knowledge, have to be assessed not by the participants of the working group themselves but by a quality assessment board of the standardization body or by public consultations via established draft standards portals. Here, the potential implications of standards for solving societal problems, e.g., in companies, and scientific challenges, e.g., related to measurement, have to be assessed. Building on Landry et al. (2001), it also implies extending the boundaries of standardization as a type of transdisciplinary research project



**Fig. 1** Standardization as transdisciplinary knowledge production and transfer

into the realms of both science in research organizations (Blind and Gauch 2009) and practice in companies as well as their implications for target groups, such as users and consumers.

Supposing the assessment of the draft standards has been positive, the final standards, including their integrated and newly produced knowledge, then have to be disseminated among the target groups, which have not been involved in the previous steps. Here, different media channels might be used, as well as meetings with representatives of target groups or participation in workshops or other events.

Finally, with the implementation of standards in companies and other organizations, the new knowledge is used in the societal realms. Complementary to this, their application in research organizations leads to their usage in the scientific realm (Blind and Gauch 2009). Hoffmann et al. (2019) suggest a further differentiation of the different steps of knowledge utilization presented by Landry et al. (2001). Here, stakeholders in the scientific and societal realm might implement the developed standards and be referenced—less in scientific papers—in regulatory documents, like European Directives. There might even be recursive relationships between standards and regulations, e.g., as revealed by Gottinger et al. (2023) in the area of bioeconomy. Overall, standards can influence future decision-making by researchers, industry practitioners, and other organizations involved in initiating new research programs or innovation activities.

Eventually, the circle might be closed by considering a recursive feedback loop (see also Blind and Gauch 2009), because the implementation of standards both in the scientific and the societal realm might create follow-up scientific and societal challenges. They can be solved either by the revision of existing or the development of new standards

within a subsequent cycle of transdisciplinary standardization processes.

Figure 1, which follows the graphical design of Pohl et al. (2021), displays the different steps of standardization as transdisciplinary knowledge production and transfer, as well as their positioning in the realms of science and practice.

## Methodological opportunities

Empirical validation of the presented conceptual model is a very challenging endeavor. The methods applied in transdisciplinary research are challenged in terms of their quality (Lang et al. 2012). Analyzing more than 100 projects, Pärli (2023) finds that the quality of the processes and methodologies have the most decisive influence on the effects of transdisciplinary research. Case studies have been the dominant methodological approach in the past (e.g., Brandt et al. 2013). Adler et al. (2018) make further progress in discussing the knowledge transfer across cases of transdisciplinary research, comparing it, e.g., with approaches utilized in basic or applied research. They propose considering the analogy of cases, which requires assessing similarities and dissimilarities of cases. Surveys are also increasingly being carried out, e.g., by Jacobi et al. (2022), who conducted surveys among participants of transdisciplinary research projects.

Related to standardization, in addition to case studies (e.g., Wiegmann et al. 2017; Schleifer et al. 2022), surveys are much more common (e.g., Blind and Heß 2023). However, there is also the option to apply indicator-based approaches relying on databases.

Starting with the standardization process, there is already a long tradition of case studies, which are particularly

suitable for reporting and analyzing specific processes of developing standards (see Swann 2000, and more recently, Wiegmann et al. 2017). They reveal the stakeholders involved, their interests and inputs, and also the negotiation processes. In contrast to transdisciplinary research in general, where surveys are quite rare (Brandt et al. 2013), standardization processes are also targeted by large-scale surveys (e.g., Blind and Heß 2023). These aimed at experts or organizations inquiring about drivers and barriers (Blind and Gauch 2009; Blind et al. 2018, 2022a) to get involved, but also the exchange of knowledge and the negotiations during the processes (Heß and Blind 2024). Finally, there are project databases set up by SDOs to track the processes and their progress. However, only a few bodies make some of the process data available (Baron and Spulber 2018).

The results of transdisciplinary processes are scientific papers that document concepts and strategies, as well as other types of artifacts, such as prototypes (Lang et al. 2012). Regarding standardization as a transdisciplinary process, the results are standards and related documentation, which make case studies and surveys inappropriate. Standards are documented in full-text databases, which are only partly accessible without payment, e.g., by the European Telecommunication Standards Institute (ETSI) (see Baron and Spulber 2018 for further information about available documents), or at least their metadata is made available in a proprietary way (e.g., in NAUTOS offered by the publishing unit of the German standardization body DIN), or for free by the International Organization for Standardization (ISO) (<https://www.iso.org/obp/ui#search>). In contrast to scientific publications, standards generally do not list the involved contributors as authors, although an indirect possibility for this does exist. For this purpose, standard-relevant publications can be used as a complement to the already-known SEPs (Bekkers et al. 2023), which are another input into standards. These are scientific publications that are listed in the bibliography of standards (Blind and Fenton 2022). From both SEPs and standard-relevant publications, the inventors or the authors and their institutions can be identified on whose contributions standards are based. From the minutes of standardization processes, Kang and Motohashi (2015) derive that direct participation increases inventors' likelihood of their patents being accepted as SEPs. Similarly, interviews with authors have revealed that most of the referenced authors have been actively involved in the standardization processes or have been consulted as external advisors (Blind and Fenton 2022). By identifying inventors' or authors' affiliations, it is possible to assess—at least partly—the transdisciplinary character of the standardization process.

Furthermore, the coverage of patent classifications or scientific fields can provide further insights into what content is relied upon and whether this can be linked to sustainability in general or to the SDGs in particular. Overall, the analysis

of the SEPs and the scientific references allows us to identify which scientific or societal problems and their related knowledge base triggered the initiated standardization process in which the referenced authors and their institutions have been involved. In addition to the results of the standardization processes, the text body of standards themselves can also be analyzed. However, full-text analyses have generally not been conducted because of limited access. Related to transdisciplinarity, such investigations could be an option to determine the integration of the different types of knowledge inputs and diverging interests.

Finally, implementing standards can be analyzed via case studies, surveys, or even databases, which opens a broader spectrum of methodological opportunities compared to traditional transdisciplinary research. Starting with case studies, we can distinguish between the implementation of a specific standard in a specific context, e.g., the banking industry (Dinçkol et al. 2023), the integration of different standards either in a product, like a laptop (Biddle et al. 2010), or in a specific company (e.g., Ploschka 2015). Whereas the previous examples address the realm of practice, there are also individual examples of standards beyond the well-known quality and environmental management standards (Pohle et al. 2018) referenced in scientific publications. Eventually, this closes the loop on the left-hand side of Fig. 1, starting from standard-relevant publications.

Surveys not only address participation in standardization processes but also the implementation of standards. In addition to surveys explicitly focused on standardization, which asks for companies' implementation of standards (Blind and Müller 2020), the German edition of the Community Innovation Survey had a similar section (Rammer et al. 2016). Finally, different types of databases exist that can provide information about the implementation of standards. First, in particular, larger companies have internal databases about the standards they have implemented in their products or processes (e.g., Ploschka 2015). However, they are generally not accessible to researchers. On an aggregate level, ISO regularly collects certifications related to the management system standards (see, e.g., Blind 2019), like ISO 9001. Certifications confirm via a third party, a certification body, that specific organizations have correctly implemented these standards. The data provided by ISO allow analyses at country and sector levels. Specific certification bodies also disclose the certifications awarded to specific organizations. However, the review by Manders et al. (2016) reveals a rather ambivalent relationship to innovation. Recently, web mining to collect information on companies' web pages has also been used to identify the mentioning of standards. Mirtsch et al. (2021) have performed such an analysis for ISO/IEC 27001, an international management system standard on information security. They validated their results with certification data, which even allows the distinction between

the diffusion of standards traced via web mining and their specific use confirmed by third-party certification.

In summary, and as displayed in Table 1, the review of studies about the standardization process, the standards themselves, and their implementation reveals case studies, surveys, and the analysis of databases as different methodological opportunities to investigate their interdisciplinary character. Specific case studies of specific standardization processes can certainly identify the most detailed information about the stakeholders and their different interests compared to surveys and databases. To analyze the standards themselves, databases—preferably of full texts—are needed. With regards to the implementation of standards, again, all three methodological options are feasible and can be selected according to the objective of the transdisciplinary research.

## Conclusion

Based on the existing models of transdisciplinary research and insights on standardization processes and the implementation of standards, we have developed, in a first step, a conceptual model of standardization as a mode of transdisciplinary knowledge production and transfer via the production, dissemination, and implementation of standards. In the second step, we addressed the methodological challenge in transdisciplinary research by presenting different approaches to the analysis of standardization processes, results, and their implementation. These opportunities allow us to address various research topics relevant to transdisciplinary research, which we elaborate on in the following section.

Already, Jahn et al. (2012), followed by Brandt et al. (2013), distinguish transdisciplinary research projects into three process phases. First, the problem identification and structuring can be analyzed in the context of standardization, e.g., based on new work item proposals submitted to the standardization bodies. Here, collaboration with SDOs, which have the full texts of the not always publicly available standards, is needed. Second, the co-creation of solution-oriented and transferable knowledge via the standardization process can be analyzed based on the minutes of standardization processes and the scientific publications referenced in standards, because they reveal relevant inputs from different stakeholders from both the science and the societal realm. First, evidence derived from the latter confirms the transdisciplinary character of standardization processes (Blind and Fenton 2022). However, further options exist to expand the research based on these publications, e.g., by considering their interdisciplinarity and linking them to transdisciplinarity. In the case of co-publications, further in-depth studies are possible. Another piece of information we have not yet considered is the references to regulation in standards,

**Table 1** Methodologies to analyze standardization as transdisciplinary knowledge production and transfer

Stages	Case studies	Surveys	Databases
Process	Observation of single standardization processes within SDOs, consortia, or companies	Surveying experts and organizations involved in standardization, e.g., the German standardization panel (Blind and Müller 2020), Community Innovation Survey (Rammer et al. 2016)	Internal databases of SDOs or openly available minutes of meetings and communication between involved stakeholders
Result	n/a	n/a	Standards databases with full text (mostly proprietary, but also available open access), metadata (NAUTOS, ISO incl. references (Blind and Fenton 2022; Gottinger et al. 2023; SEPs)
Implementation	Cases of standards implemented in products (Biddle et al. 2010), companies (Ploschka 2015), or industry (Dinçkol et al. 2023), but also science	Surveying experts and organizations involved in standardization, e.g., the German standardization panel (Blind and Müller 2020), Community Innovation Survey (Rammer et al. 2016)	Company-internal databases (Ploschka 2015); ISO survey of certifications; web mining (Mirtsch et al. 2021; Blind et al. 2023)

which are essential in practice and in our conceptual model. Finally, the implementation of standards as results of standardization processes into practice, again, both in the scientific and societal realm, can be traced either via certification databases focused on specific, mainly well-established management standards or via web mining for all types of standards (e.g., Mirtsch et al. 2021), as well as in scientific publications referencing standards.

However, even more recent findings of transdisciplinary research can be applied to standardization and analyzed via different approaches. For example, Jacobi et al. (2022) point to the duality of science and society in transdisciplinary research, which can be confirmed for standardization based on various surveys (e.g., Blind and Gauch 2009 or Blind et al. 2018). Furthermore, the imbalances, at least those related to the involvement of different stakeholders (e.g., Blind and Heß 2023), can be explained by the initially industry-driven character of standardization (Blind and Mangelsdorf 2016). Within the European Union (EU), Regulation 1025/2012 on European standardization aims to achieve a balanced participation of stakeholders representing interests of societal relevance, such as environmental, consumers' and workers' interests, because standards have several impacts on society and, therefore, it is necessary to consider their input in their development. Therefore, the European standardization organizations are encouraged to facilitate and support the representation and effective participation of these stakeholders. Complementary, some European stakeholder organizations representing environmental or consumer interests receive even funding by the European Union. Finally, the recently published Code of Practice on Standardisation by the European Commission (2023) is an attempt to strengthen explicitly researchers' and research organizations' involvement in standardization, which might create further tensions between stakeholders from the realm of science and practice. Moreover, even the tensions between societal and academic outputs of transdisciplinary research can be investigated related to standardization, not only via case studies and surveys but also by considering the contents and referenced sources of standards databases (Blind and Fenton 2022) and the references they receive in scientific publications. Another question that may need to be answered in the future could be whether the degree of transdisciplinarity or the stressed broader inclusiveness as proposed in the United States Government National Standards Strategy for Critical and Emerging Technology by the Biden-Harris Administration (2023), as a kind of input legitimacy (Botzem and Dobusch 2012), has positive implications also on the diffusion of standards, as claimed by Jacobi et al. (2022) for transdisciplinary research results. Therefore, the presented conceptual

model and the elaboration of various methodological approaches represent only the starting point for a more comprehensive analysis of standardization as transdisciplinary knowledge production and transfer to address various research topics in the future. These new insights might also provide meaningful contributions to transdisciplinary research as such.

Finally, standardization processes can benefit from lessons learned in performing transdisciplinary research projects.<sup>6</sup> Here, we rely on the findings of Roux et al. (2017) and Bergmann et al. (2021). First, as in transdisciplinary research, the right balance between scientific and societal objectives has to be achieved in standardization.<sup>7</sup> In addition, in standardization processes, the focus is on the latter, so the scientific base should be improved (see Blind and Fenton 2022). Consequently, the practitioners' needs and limitations have been considered, which is also a necessary requirement in the development of standards to promote their implementation. Furthermore, the long-term orientation of transdisciplinary research projects improves their success, aligning with the long-term standardization processes performed within established working groups or technical committees. In contrast, the implementation orientation, which might be a challenge in transdisciplinary research, should be no issue in standardization, because the involved stakeholders should be interested in implementing the developed standards. The suggestion by Roux et al. (2017) that researchers should perceive themselves as co-learners and not masters of their knowledge domains is a constructive recommendation for researchers involved in standardization processes to reach a faster consensus with industry representatives and to facilitate the implementation of standards in practice. This is also in line with avoiding biases in selecting participants, the perception of the superiority of scientific knowledge, and the selection of simple solutions for wicked problems, which confirm the status quo. Here, active communication of diverging views helps develop a 'collaboration culture,' which is generally the case within standardization working groups and committees.

<sup>6</sup> The authors thank an anonymous reviewer for the suggestion to include this paragraph.

<sup>7</sup> On the one hand, the above-mentioned EU regulation promoting the involvement stakeholder organization in standardization and their funding by the European Union are standardization-specific approaches, which are not appropriate for transdisciplinary research. On the other hand, the findings in Bergmann et al. (2021) and Roux et al. (2017) related to transdisciplinary research are not effective to limit the dominant role of industry in standardization.

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## Declarations

**Conflict of interest** The author has no competing interests to declare that are relevant to the content of this article.

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