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The Socio-Ecological Black Box of Digital Media Technologies: An Invisible Sustainability Issue in Pre-Service Teachers' Media Practices

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Abstract

The socio-ecological costs of digital media technologies—resource extraction, energy-intensive infrastructures, and electronic waste—remain largely invisible in everyday life and in education. Drawing on practice theory and science and technology studies on opacity, this article introduces the "black-box problem" as an analytical lens for understanding why digital technologies are so rarely enacted as objects of sustainability concern. Distinct from the algorithmic black box, which concerns the opacity of code and data, the socio-ecological black box concerns the opacity of the material and social relations that a digital device or service presupposes. This study is based on a qualitative analysis of 23 semi-structured interviews with pre-service teachers across five higher-education sites in Germany, coded using Grounded Theory procedures and interpreted along practice theoretical lines. The findings show that the black box operates across four interlocking dimensions—production, use, disposal, and the absence of recognisable alternatives—and that the same pre-service teachers who reason competently about sustainable food, mobility, and clothing largely lack ecological categories with which to evaluate digital devices and services. This pattern is domain-specific and is not adequately explained by individual disinterest or by a general lack of sustainability knowledge. Read through accounts of digital capitalist externalisation, weak public discourse, and missing regulation, it is interpreted here as a structurally produced blind spot rather than as an individual knowledge deficit. For Education for Sustainable Development and media education, the implications are direct: pre-service teachers, as future multipliers, require infrastructural literacy that renders the material substrate of the digital available for critical, action-oriented reflection.

Keywords: digital (un)sustainability; media education; education for sustainable development; practice theory; media practices; teacher education; pre-service teachers; socio-ecological black box of digital media technologies

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1. Introduction

Every search query, video stream, and cloud back-up rests on a material substrate that its users almost never see: mined rare-earth metals, transoceanic cables, and energy-intensive data centres, followed, at the end of a device's life, by streams of electronic waste. The information and communication technology (ICT) sector is now estimated to account for a non-trivial and rising share of global greenhouse gas emissions, and the volume of e-waste generated worldwide continues to grow faster than documented recycling capacity [1,2]. Yet in everyday experience, the digital presents itself as weightless and immaterial—a

mismatch between the subjective effortlessness of a tap on a screen and the very real energy and matter that the action mobilises.

This mismatch serves as the analytical starting point for the present study: across sustainability discourse, education, and public debate, relatively well-established vocabularies have been developed for discussing the environmental costs of food, mobility, and clothing. Consumers recognise organic and fair-trade labels, distinguish regional from imported produce, and can weigh cycling against driving. For digital media technologies, no comparably established repertoire of orientation exists. The devices that mediate contemporary life—and, increasingly, contemporary teaching and learning—are treated as if they were almost ecologically neutral by default [3]. I call this the *black-box problem*: the socio-ecological dimensions of digital media technologies are, for most users, systematically opaque, and this opacity structures what people can and cannot do in relation to them.

The problem is of particular importance in education. Digitalisation and Education for Sustainable Development (ESD) are two of the most prominent transformation agendas in contemporary schooling, yet they are usually pursued in parallel rather than in relation to one another. The United Nations' 2030 Agenda frames both: SDG 4 (quality education), SDG 12 (responsible consumption and production), and SDG 13 (climate action) converge precisely where the material footprint of digital media meets the classroom [4]. Where the two agendas do meet, the digital tends to appear only as a means of sustainability education rather than as an object whose own sustainability is at stake. The socio-ecological cost of the devices used in teaching and learning remains outside the frame.

Pre-service teachers occupy a strategically significant position in this configuration. As future multipliers, they will shape whether and how the coming generation learns to perceive the material substrate of digital life. If their own media practices leave the socio-ecological dimensions of technology invisible, that invisibility is likely to be reproduced in their teaching. Understanding how prospective teachers perceive—or fail to perceive—the sustainability of the digital is therefore not a marginal question but a condition for any serious integration of media education and ESD.

Against this background, this article pursues one guiding question: How do pre-service teachers perceive and practically relate to the socio-ecological dimensions of digital media technologies, and how does the (in)visibility of these dimensions structure their sustainability-related media practices? The question is approached through a qualitative study of 23 semi-structured interviews, interpreted with the conceptual tools of practice theory and of science and technology studies on opacity. The contribution is threefold. First, the article develops the black-box problem as an analytical concept that specifies socio-ecological opacity, distinct from the more familiar algorithmic black box. Second, it provides empirical evidence that this opacity is differentiated into four interlocking dimensions—production, use, disposal, and the absence of recognisable alternatives. Third, through a within-subject contrast with other consumption domains, it shows that the black box cannot be reduced to an individual knowledge deficit, develops a structural interpretation of this domain specificity, and draws out the consequences for teacher education and ESD.

The remainder of this article is organised as follows. Section 2 outlines the theoretical framework, followed by a description of the research design in Section 3. Section 4 presents the findings across the four dimensions of the socio-ecological black box of digital media technologies and contrasts them with other sustainability domains, before turning, in Section 4.6, to deviant and contrasting cases. Section 5 discusses the implications, before Section 6 concludes.

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2. Theoretical Framework

2.1. The Material Substrate of "Immaterial" Media

The premise that digital media are immaterial has been thoroughly dismantled by a body of work often grouped under the heading of media materialism. Parikka's notion of a *geology of media* reframes screens and servers as concentrations of mined matter—metals, minerals, and rare earths whose extraction is inscribed with environmental damage and geopolitical asymmetry [5]. Cubitt extends the argument to the energy and waste dimensions, insisting that digital media are finite in a double sense: they draw on finite resources and they produce finite, disposable objects [6]. Crawford's account of artificial intelligence as an "extractive" industry adds the labour and computational infrastructure that underpins contemporary platforms; the environmental cost of artificial intelligence in particular has drawn increasing critical attention [7,8]. Across these accounts, the recurring theme is that the apparent lightness of the digital is an effect of distance: the sites of extraction, computation, and disposal are geographically and perceptually removed from the sites of use—so dispersed across space and time that the aggregate footprint takes on the character of a hyperobject, exceeding the scale of ordinary perception [9].

Quantitative estimates lend weight to the qualitative claim: analyses of the climate impact of ICT place the sector's share of global emissions in a range that is significant, contested, and—on current trajectories—expected to grow rather than shrink [1]. Studies of digitalisation and energy consumption, and the broader field of research on ICT for sustainability, document how efficiency gains at the device level are repeatedly offset by rebound effects at the systemic level, as cheaper and faster computation induces more of it [2,3,10]. The material footprint of the digital is therefore neither trivial nor self-correcting; it is a first-order sustainability problem that happens to be exceptionally well hidden.

2.2. The Black Box as an Analytical Concept

The metaphor of the black box has a settled meaning in science and technology studies. For Latour, black-boxing is the process by which a working assemblage of people, artefacts, and knowledge becomes so stabilised that users attend only to its inputs and outputs, never to its inner workings [11]. Pasquale's *black-box society* applies the figure to algorithmic systems, foregrounding the opacity of the code and data that govern search, credit, and reputation [12]. Both usages concern epistemic opacity—what cannot be known about how a system operates.

This article proposes a distinct specification—the *socio-ecological black box of digital media* technologies (Figure 1). What is opaque here is not the algorithm but the material and social relations that a digital device or service presupposes—the conditions of its production, the energy of its operation, the fate of its disposal, and the space of its possible alternatives. This opacity is not merely epistemic; it is practical. It concerns not only what users fail to know but what, given that failure, they are unable to do. The socio-ecological black box thus sits at the intersection of a knowledge problem and an action problem, and it is precisely this intersection that a practice theoretical lens is well suited to analyse.

Three features distinguish this specification from existing uses of the black-box figure, and it is their combination rather than any one of them that constitutes the contribution of this article. First, it transfers the figure from the epistemic algorithmic register, where it names the opacity of code and data, to a material ecological one, where it names the opacity of resources, energy, labour, and waste. Second, it grounds the figure in practice theory: the socio-ecological black box is not only a property of the artefact but a condition continuously reproduced in domesticated everyday practices, as Section 2.4 sets out. Third, it draws an educational consequence from this reframing in the concept of infrastructural literacy (Section 2.6). The specification also connects to a long-standing observation in the study of

infrastructures, namely that infrastructure becomes perceptible when it fails and recedes from view when it works [13]; the socio-ecological black box names a case in which the smooth functioning of digital infrastructures renders their planetary preconditions imperceptible to those who depend on them. The forms of opacity at issue may be distinguished further along the lines proposed for algorithmic systems, where deliberate concealment, the technical competence of the observer, and sheer scale and complexity operate as separate sources of non-transparency [14]. In the socio-ecological case, all three are at work, and the third—the geographical and temporal dispersion of extraction, computation, and disposal—is the least tractable by disclosure alone.

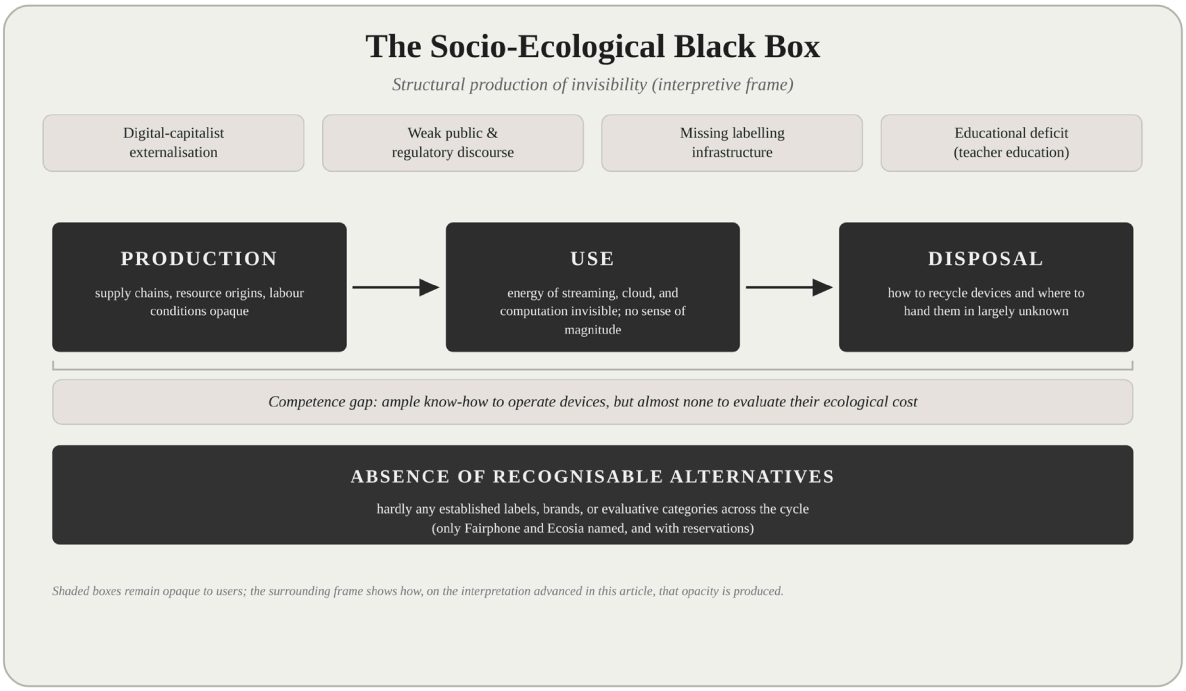


Figure 1. The socio-ecological black box of digital media technologies. The three shaded life-cycle stages (production, use, disposal) and the absence of recognisable alternatives remain opaque to users; the competence gap denotes the mismatch between operational know-how and evaluative capacity; the surrounding frame names the structural conditions through which, on the interpretation advanced here, the opacity is produced. Source: author.

2.3. Media Practices: A Practice Theoretical Perspective

To ask what people do with and in relation to digital media is to situate the inquiry in the field of media practices, which studies how social actors appropriate media across contexts. The field rests on a sociological foundation, drawing above all on the practice theories of Schatzki and Reckwitz. For Schatzki, a practice is an open-ended, spatially and temporally dispersed "nexus of doings and sayings" [15]: it extends across time and space and binds together what people do with what they say. Practices are, on this account, irreducibly collective—organised constellations of many people's activities rather than isolated individual acts [15]—and it is in the field of such practices and their material arrangements that Schatzki locates the social itself [16]. Reckwitz's influential formulation specifies their internal make-up: a practice is a routinised type of behaviour whose interconnected elements include bodily and mental activities, things and their use, background understanding, know-how, and states of emotion and motivation [17]. Practices are therefore socially shared, knowledge-dependent routines rather than punctual individual actions [17].

Following the "practice turn" in social theory [18], media and communication research developed a corresponding programme over the past two decades. Couldry reframed media themselves as an open set of practices oriented around media, and made the field's guiding question the deceptively simple one of what people are actually doing in relation to media across the full range of everyday situations, arguing that only a practice theoretical perspective can show how media become embedded in social and cultural life [19]. A closely related strand—media appropriation and domestication research—examines how people integrate media technologies into their everyday and domestic routines, treating the user not as a passive recipient but as a sense-giving agent who tests media offerings and either takes them up or refuses them [20]. This everyday integration is precisely the register in which the present study's pre-service teachers operate: their devices are thoroughly domesticated, woven into study, leisure, and social life as unremarkable equipment.

2.4. From Everyday Appropriation to "Acting on Media"

Within this everyday register, media practices differ in how far the technologies themselves become an explicit object of action—a distinction some scholars mark as one between merely mediating practice, in which media are woven into everyday life, and practising media, in which media themselves are actively worked upon [21]. Kannengießer and Kubitschko capture the more reflexive pole with the concept of *acting on media*, which names the efforts of a wide range of social actors to take an active part in shaping the media organisations, infrastructures, and technologies woven into the fabric of everyday life [22]. Acting on media covers practices in which people consciously work on media technologies—repairing them, choosing fair alternatives, contesting their conditions of production—and thereby transforms not only the artefacts but also, potentially, the wider society [22]. Such practices are often, though not always, political: the material technology is itself made an object of concern, and, like other political action, acting on media is embedded in and reproduces constellations of power bound up with gender, class, age, and education [22]. More broadly, a practice theoretical lens reveals how social actors—individuals as much as collectives such as social movements—participate, articulate themselves, and contest dominant viewpoints through their media practices [23].

The socio-ecological black box is precisely what forecloses acting on media in the sustainability register: it holds the material substrate of digital technologies outside the field of concern, so that devices are appropriated and domesticated but never taken up as something one might act upon. Shove and colleagues' tripartite model—practices as configurations of materials, competences, and meanings [24]—locates the foreclosure precisely. The media practices at issue are richly endowed with materials (devices, networks) and saturated with meanings (convenience, identity, connection); what is missing is the sustainability-relevant competence. Users command ample know-how for operating devices and almost none for evaluating their ecological cost—a competence gap that, as the analysis will show, is patterned across production, use, disposal, and the search for alternatives.

Practice theory further insists on the materiality of practices, objecting to the "dematerialisation of the social" in much social and cultural theory and foregrounding both the acting body and the things that are constitutive elements of any practice [17]. Kannengießer's work on consumer-critical and sustainability-oriented media practices brings this materialist emphasis to the digital domain, analysing repair and fair production as forms of acting on media through which the materiality of technology is engaged and reflected [25,26]. This framing anticipates a mirror image that the analysis below makes visible in the data: where acting on media is foreclosed, the counterpart to deliberate waste avoidance is an involuntary accumulation of unusable devices. Reading the black box through practice

theory thus reframes it, not as a state of mind but as a property of practices, a competence gap that is enacted and reproduced yet remains, in principle, transformable.

2.5. Digital Capitalism and the Production of Invisibility

Why is the socio-ecological cost of the digital so effectively hidden? The answer developed here is a structural one: critical accounts of digital capitalism describe an economic order that depends on the continuous externalisation of environmental and social costs onto distant places, future times, and non-consuming others [27], and work on carbon capitalism and communication has traced how the media and communication industries are entangled in this carbon-intensive order [28]. Lessenich's analysis of the externalisation of society generalises the mechanism: the prosperity of some is systematically underwritten by costs displaced onto others and rendered invisible to the beneficiaries [29]. Brand and Wissen sharpen the everyday dimension of this mechanism with their concept of the imperial mode of living: the appropriation of distant resources, sinks, and cheap labour is inscribed into ordinary, largely unreflected practices, while the concrete conditions under which commodities are produced are rendered invisible at the very places where they are consumed [30]. Applied to media technologies, externalisation names the process by which extraction, emissions, and e-waste are pushed out of the user's perceptual field, so that the device arrives—and departs—as if it had no history and no afterlife.

On this reading, the invisibility documented in the data is not a contingent gap that better information campaigns would simply close. It is a produced condition, sustained by the absence of labelling infrastructures, the weakness of public and regulatory discourse on digital sustainability, and the commercial interest in presenting devices as clean, seamless, and endlessly upgradable [3]. The black box, in short, is, on this account, manufactured. This has an important implication for education: interventions aimed solely at individual awareness will run up against a structure that continually reproduces the very opacity they seek to dispel—which is why proposals for a more sustainable digital society increasingly stress structural principles such as digital sufficiency rather than efficiency alone [31].

2.6. Media Education Meets Education for Sustainable Development

Education for Sustainable Development aims to cultivate the competences needed to act toward a more sustainable future—systems thinking, anticipatory and critical competence, and the capacity for responsible action, as codified in competence frameworks such as GreenComp [32] and in the UNESCO roadmap for ESD [33,34]. Media education, for its part, has long concerned itself with the critical analysis of media, including their institutional and economic conditions. The intersection of the two fields is, however, thinly developed. Where digital media appear in ESD, they usually appear instrumentally, as tools for teaching about sustainability, and where sustainability appears in media education, it is often subordinated to questions of content, representation, and use rather than of infrastructure and matter—even as scholarship on education and technology increasingly insists that educational technology carries its own material and environmental costs [35]. That this intersection is thinly developed is not merely an impression; two systematic reviews have searched the adjacent terrain and report emptiness at precisely this point. Kuntsman and Rattle's review of the literature relating digital communication to environmental sustainability finds the material damage of digital communication to be paradoxically under-theorised, and describes the resulting omission as a material blind spot sustained by what they term digital solutionism [36]. In educational research, a review screened 2099 articles for frameworks that integrate digital media in line with the ecological, economic, and social dimensions of sustainability, and found none that met its inclusion criteria. The same study reports that GreenComp treats educational technology only as

an outlook on possible learning benefits, and that the European framework for the digital competence of educators confines the environmental impact of digital technologies to one aspect of a single competence [37]. Programmatic counter-positions exist within media education—López's ecomedia literacy places ecology at the centre of the media curriculum [38]—but they argue at the level of curriculum and pedagogy rather than examining how learners themselves reason about the material substrate of their own media practices. The gap is therefore a specific one: what is missing is neither attention to the ecological costs of digital technologies nor proposals for greening media education, but empirical evidence on how those who will teach with these technologies perceive, or fail to perceive, their material preconditions.

The black-box problem sits exactly in this under-theorised gap: rendering the socio-ecological dimensions of digital media available for reflection requires a form of infrastructural literacy—the capacity to perceive, question, and act upon the material and social relations that digital practices presuppose [3]. Because pre-service teachers are the multipliers who will decide whether such literacy is passed on, their own perceptions and practices are the appropriate empirical site at which to examine whether, and how, the black box might be opened. It is to that site that the analysis now turns.

3. Materials and Methods

3.1. Research Approach and Rationale

Because this study is concerned with the meaning constructions of pre-service teachers and with the reconstruction of their media practices, a qualitative approach to the research question was appropriate. Qualitative research, in Kruse's formulation, seeks to understand complex social phenomena and to reconstruct subjective patterns of interpretation [39]; both aims are central here, where the object of inquiry is not the measurable prevalence of a behaviour but the way in which prospective teachers make sense of—and fail to make sense of—the socio-ecological dimensions of the digital.

The analysis is located in the constructivist tradition of Grounded Theory as developed by Charmaz [40]. This choice is epistemological rather than merely procedural: categories are not discovered in the data but constructed in the interaction between the material, the prior theoretical knowledge brought to it, and the analytic process. The procedural vocabulary used in Section 3.3 to describe the coding—open, axial, and selective coding—follows the sequencing of Strauss and Corbin [41], which has become the established descriptive language for coding processes in German-language qualitative research. The two references therefore operate at different levels: the epistemological framing of the analysis (Charmaz) and the description of its procedural steps (Strauss and Corbin). Where the two traditions diverge, above all on whether categories are found in or constructed from the data, the constructivist position governs, with consequences for the reflexive account given in Section 3.4. Grounded Theory was chosen for two reasons. First, it permits an approach to the material that is open yet theory-guided: categories are constructed in close engagement with the data, while a body of prior theoretical knowledge is allowed to sensitise the analysis. In the present study, the practice theoretical framework set out in Section 2—with its attention to the interplay of materials, competences, and meanings—supplies precisely this theoretical sensitivity, orienting the coding without predetermining its results. Second, Grounded Theory is a theory-generating procedure aimed at developing an empirically anchored ("grounded") account of the phenomenon; in these procedures, theoretical statements are treated as communicable propositions derived from correctly executed empirical operations [41]. Through this procedure, this study contributes to educational science sustainability research while also generating findings relevant to the neighbouring fields on which its theoretical dimensions draw—research on media practices

and on the materiality of media technologies in particular. The present article focuses on one cross-cutting theme—the socio-ecological black box—within a larger study of the sustainability-related media practices of pre-service teachers, further results of which will be reported separately.

3.2. Sampling and Data Collection

Participants were recruited through a combination of maximum-variation and theoretical sampling. The initial selection aimed at the widest possible variation in the sociodemographic background of the pre-service teachers—with respect to gender, age, educational biography, and sustainability-related activities—so that the analysis could confront the widest possible range of perspectives on sustainability-related media practices. As analysis proceeded alongside data collection, subsequent sampling decisions were additionally guided by the categories emerging from the material, in line with the cyclical logic described below [41]. The resulting corpus comprises 23 semi-structured interviews with pre-service teachers enrolled in teacher education programmes across five higher-education sites in Germany. Transcripts are anonymised and referenced here by a site-and-interview code; for example, H1:6 denotes site 1, interview 6, followed by the segment number (e.g., H1:6, 166). The interviews addressed participants' everyday media practices and their engagement with sustainability: an open question invited participants to describe their everyday sustainability practices, while specific questions addressed the acquisition, use, and disposal of digital devices and the sources from which participants obtained information on the topic. Table 1 reports the resulting composition of the sample.

Table 1. Sample characteristics, aggregated by site. Sites are anonymised and reported in aggregate so that individual participants cannot be identified at sites with few interviews. Semesters are counted separately for Bachelor's and Master's programmes; "Master" denotes semesters of the Master's programme. For the same reason, gender is reported for the total sample only: 19 participants were female and 4 male.

Site	*n*	Teaching Degree Programme	Subject Groups	Semester of Study (Range)	Age Range
H1	8	Academic-track secondary, Gymnasium (ISCED 2–3); primary (ISCED 1)	German, English, French, geography, history, ethics, religious education, mathematics, art, music, Sachunterricht (integrated science and social studies)	7th–10th	22–27
H2	2	Academic-track secondary, Gymnasium (ISCED 2–3)	Geography, French, economics, biology	6th–12th	24
H3	3	Vocational education and training (ISCED 3)	Business and administration, German, health and nursing care, computer science, ethics	1st–8th	25–32
H4	7	Primary (ISCED 1); lower secondary (ISCED 2)	German, mathematics, English, history, music, physical education, Sachunterricht (various emphases)	3rd–2nd Master	21–31
H5	3	Special needs education; primary (ISCED 1); academic-track secondary, Gymnasium (ISCED 2–3)	German, Sachunterricht, mathematics, arts education	2nd–4th Master	22–35

Consistent with the logic of Grounded Theory, data collection was organised cyclically [42]: the data gathered first were analysed to generate initial insights, which were then compared with existing knowledge and fed back into the ongoing collection procedure—for instance, into decisions about further sampling. Because interviews were already being analysed while the collection phase was still underway, data collection could be concluded when, in the author's assessment, further interviews no longer yielded new aspects for the categories reported here (theoretical saturation in the sense of [41]). Data were collected

between December 2022 and May 2025. The length of this period follows from the staggered field access to the five higher-education sites and from the cyclical design described above, in which analysis proceeded alongside collection. Participants were approached through lecturers at the participating institutions. All interviews were conducted by the author as online interviews via Zoom or Webex and lasted between 20 and 54 min. The guide was structured in three thematic blocks—sustainability-related everyday practices, sustainability-related media practices, and perspectives on their future profession—and moved in each block from open narrative prompts to more specific questions; the block on media practices followed the sequence of acquisition, use, and disposal. The guide contained no question on alternatives. Its open questions on acquisition, use, and disposal left room for participants to raise alternatives but did not prompt them; the fourth dimension reported in Section 4 emerged in the course of coding (Section 3.3). The full guide has been made available to the editors and reviewers and can be obtained from the author on request. Ethical review, informed consent, and anonymisation are reported in the Institutional Review Board Statement and the Informed Consent Statement below. All interviews were recorded digitally with the informed consent of the respondents and transcribed verbatim. The excerpts reproduced in Section 4 were translated from German by the author, with interview codes and segment numbers retained for traceability.

3.3. Coding and Analysis

After collection, the material was available primarily as interview transcripts. The analysis was carried out with the software ATLAS.ti (Versions 23–25; ATLAS.ti Scientific Software Development GmbH, Berlin, Germany), in line with the constructivist position set out in Section 3.1 [40]; a computer-assisted procedure not only facilitates coding but also supports the systematic comparison of segments. Coding proceeded through the three stages of Grounded Theory [41], which allow the material to be approached in a theory-guided manner and the meanings that the different pre-service teachers attribute to their practices to be elucidated while enabling systematic comparison across the material; in this model, the data are broken open, conceptualised, and reassembled in new ways. The resulting category system comprises seven superordinate categories—sustainability-related everyday practices; sustainability-related media practices; factors influencing everyday and media practices; understandings of sustainability and reasons given for sustainability-related practices; (non-)engagement for sustainability; school; and teacher education—within which the socio-ecological black box emerged as a cross-cutting theme, drawing principally on sustainability-related media practices (acquisition, use, disposal) and on the contrast with general sustainability practices. The complete code tree for the black-box theme is documented in Appendix A (Figure A1 and Table A1).

In the first, open coding step, inductive categories were formed: the data were broken into discrete parts, examined closely, and compared for similarities and differences. In the subsequent step of axial coding, the initially unordered codes were sorted and set in relation to one another. Finally, in selective coding, the main categories were formed through which the data were once more sorted and hierarchised. The four dimensions of the black box reported below—production, use, disposal, and the absence of recognisable alternatives—together with the cross-domain contrast, emerged as the higher-order categories of this final step. Where a claim is illustrated by a single excerpt, additional confirming segments are indicated in parentheses, indicating that the pattern is supported across multiple interviews rather than resting on a single case. The genesis of the four dimensions warrants explicit note. Three of them correspond to phases that the interview guide also addressed (acquisition, use, disposal; participants addressed production in the context of acquisition); the guide thus supplied a thematic frame within which the specific nature of each knowledge gap

was reconstructed from the material. The fourth dimension, the absence of recognisable alternatives, was not prefigured in this way and emerged in the course of coding. The asymmetry is analytically consequential. Three dimensions parallel the life cycle of a device because the object under study is a material artefact that passes through such a cycle; the fourth describes not a phase of the artefact but the space of action available to its users, and it is this dimension that contributes centrally to the structural argument developed in Section 5, which rests primarily on the within-subject contrast (Section 4.5). In the code tree, it is also the most thinly grounded of the four in open codes of its own (Appendix A, Table A1). This is appropriate to what the dimension describes rather than a weakness of the coding: it names an absence, which participants do not address as a topic in its own right but encounter while speaking about something else. Its evidence is correspondingly distributed across the codes on acquisition, use, and the contrast with other consumption domains, as Sections 4.4 and 4.6 show.

One interpretive feature warrants explicit note. The analysis deliberately foregrounds a within-subject contrast: because the same participants spoke about several consumption domains—the established domains on their own initiative, in response to an open question on their everyday sustainability practices, and digital media technologies in response to specific questions on acquisition, use, and disposal—differences in the articulacy of their reasoning across domains can be read as evidence about the domain rather than about the person. The asymmetry in prompting works, if anything, against the finding: participants articulated criteria unprompted in the established domains, but not when explicitly asked about digital devices. This design feature is central to the argument, developed in Section 5, that the black box is a structural rather than an individual phenomenon.

3.4. Reflexivity and Quality Criteria

The study was designed, conducted, analysed, and written by a single researcher, who works in media education with a research focus at its intersection with Education for Sustainable Development. During the data collection period, the author was employed at one of the five sites, held a visiting professorship at a second site until March 2023, and had occasional teaching assignments at a third. At all sites, participants were recruited in the same way, through other lecturers at the institution. Five of the twenty-three participants had attended courses taught by the author; none of these courses addressed media education in relation to sustainability or Education for Sustainable Development. For these participants, the interviewer was known to them as a lecturer; this was not concealed, and the assurance given in the consent procedure that lecturers would not learn of their participation applied to the other lecturers involved in recruitment. The argumentative profile of these five interviews does not differ from that of the others: the four dimensions of opacity and the cross-domain contrast appear in them in the same form. Three safeguards applied. Participation was voluntary, and the written request for participation stated this explicitly. All participants were informed about the nature of the interviews before agreeing to take part and all were told that declining to participate would entail no disadvantage of any kind. Under the regulations of the author's institution, the research procedure adopted in this study was not subject to mandatory ethical review; it was nevertheless reviewed retrospectively by the institution's ethics committee, which issued a positive vote (see the Institutional Review Board Statement below). Both the interview guide and the analysis were shaped by the theoretical framework set out in Section 2, which was in place before coding began: the expectation that the socio-ecological dimensions of digital media technologies are weakly developed in everyday reasoning was the analytic starting point of the study rather than a result of it. Making this explicit matters for the constructivist position adopted here, in which the categories reported below are understood as constructed in the

encounter between material and researcher rather than as found in the data. The analysis of deviant and contrasting cases in Section 4.6 serves, among other purposes, as a check on that starting expectation.

Five strategies were used to render the construction of categories traceable. First, every claim advanced in Section 4 is supported not only by the excerpt quoted but by additional confirming segments listed in parentheses; so, the support for a pattern across multiple interviews can be inspected rather than assumed. Second, the complete code tree for the black-box theme is documented in Appendix A, providing an audit trail from the open codes to the core category. Third, coding and the constant comparison of segments were carried out in ATLAS.ti, which supports systematic retrieval and comparison across all interviews; analytic memos were written throughout and used to document the development of categories. Fourth, data collection and analysis proceeded cyclically (Section 3.2), allowing for an assessment during rather than after fieldwork of whether further material no longer modified the categories. Fifth, the developing category system was discussed in a peer debriefing with a colleague, which provided an external check on the plausibility of the categories and on their fit with the material.

Two limits of this arrangement should be stated plainly. All coding was carried out by one person, and no measure of intercoder agreement was calculated. This follows from the methodological position rather than from an omission: measures of coding agreement presuppose that a coding-independent correct assignment exists, which is precisely the assumption that constructivist Grounded Theory sets aside. What such a design can offer instead is traceability and grounding, which the strategies above are intended to provide. The interpretive latitude that remains is real, and it is reflected in the limitations discussed in Section 5.5.

4. Results

Digital media technologies remain, in their socio-ecological dimensions, largely opaque to the pre-service teachers. The findings differentiate this opacity into four analytically separable but empirically interwoven dimensions—(1) the production black box, (2) the use black box, (3) disposal uncertainty, and (4) disorientation regarding alternatives—before examining, in a fifth step, how these knowledge gaps contrast with pre-service teachers' differentiated knowledge in other sustainability domains, and, in a sixth step, which cases depart from the pattern. Table 2 summarises the four dimensions before they are examined in turn.

Table 2. The four dimensions of the socio-ecological black box, with the core knowledge gap, the typical stance of pre-service teachers, and illustrative interview references for each.

Dimension	Core Knowledge Gap	Typical Stance of Pre-Service Teachers	Illustrative Interviews
Production (Section 4.1)	Supply chains, resource origins, and labour conditions opaque; hardly any criteria for evaluating manufacture	Brand loyalty and habit; durability used as a proxy; resigned acceptance of the status quo	H1:1; H1:4; H1:6; H4:5; H5:1; H1:8; H4:3; H4:7
Use (Section 4.2)	Energy of streaming, cloud, and computation, and the enabling infrastructure, invisible; no sense of magnitude	"Small-cog" powerlessness; knowledge arrives by chance and rarely guides action	H1:3; H1:5; H4:1; H5:2; H1:8; H3:3; H4:3
Disposal (Section 4.3)	How to recycle or dispose of devices, and where largely unknown; collection points not salient	Devices accumulate in drawers; data protection concerns block disposal	H1:3; H1:7; H4:1; H4:4; H5:2; H1:8; H4:7

Table 2. *Cont.*

Dimension	Core Knowledge Gap	Typical Stance of Pre-Service Teachers	Illustrative Interviews
Alternatives (Section 4.4)	No established frames of orientation; only Fairphone and Ecosia named, with caveats; no categories for software	Sense of a "large topic one can get lost in"; doubt that sustainable media use is possible at all	H1:3; H1:4; H1:6; H2:2

4.1. The Production Black Box

Although many pre-service teachers know in general terms that the manufacture of digital media technologies is associated with problematic conditions—environmentally damaging resource extraction, precarious labour, child labour—this knowledge remains abstract and remote from action. The concrete supply chain of a smartphone, the provenance of individual components, and the working conditions in particular factories are scarcely known. One pre-service teacher names this structural opacity explicitly (see also H1:1, 17; H1:3, 85; H1:5, 144; H4:2, 436; H4:4, 495; H2:1, 257; H5:2, 658; H1:8, 226; H4:3, 469; H4:7, 588):

> *"It is difficult for me to trace the conditions under which technology is produced […]. So it is hard for me to follow, and I also cannot really verify it at the point of purchase."* (H1:6, 166)

The consequence is an acquisition practice that, despite a basic sustainability orientation, applies almost no sustainability-based criteria. Brand loyalty and habit take the place of informed decision-making. Practices that do reduce the material footprint of acquisition—buying used, or declining to buy at all—are present in the corpus, but they rest on financial or habitual, rather than ecological, grounds, as Section 4.6 sets out. One pre-service teacher describes how the question of alternatives is never even posed:

> *"Especially with the decisions–I don't know. To be honest, I have never really engaged with it, but I personally prefer Apple devices, simply out of habit and because of the compatibility between them, and I have actually never asked myself whether I would use a device from another brand; it was always simply clear, without questioning it further."* (H1:1, 25)

Knowledge of the problem does not translate into an informed choice but into an almost resigned acceptance of the status quo. As one pre-service teacher puts it, awareness of corporate malpractice coexists with a felt absence of alternatives: the participant knew that acquiring the device was "not sustainable," yet did not know what the alternative would be "apart from second-hand," so that "for lack of alternatives outside the second-hand sphere, that was not a big aspect when acquiring the devices" (H1:4, 109). This resignation recurs for digital media technologies in a way it does not in the participants' accounts of food or clothing, and participants themselves link it to the absence of alternatives that are visible or established within their horizon of orientation.

The same constellation recurs where perceived durability is pressed into service as a proxy for sustainability. One pre-service teacher reports trying to buy devices that last as long as possible while explicitly bracketing the question of how they were produced: a MacBook or an iPhone is chosen because such devices are assumed to last longer than a discount-brand laptop, "I don't know how they were produced" (H4:5, 527). The presumed longevity of certain products stands in for the absence of more differentiated criteria for evaluating manufacture. The practical consequence of the gap is stated with disarming candour: "I understand very little about sustainability and media use. […] I know that this is quite problematic. I don't quite understand why and what is behind it" (H5:1, 616). The awareness is present, the substance that would enable concrete action is not. A further

participant confirms this pattern for acquisition: when buying a laptop, sustainability "played rather less of a role," the aim being "just... a laptop for my studies that works well," without "thinking much about sustainability at all" (H1:2, 60).

Occasionally, pre-service teachers report encountering information about production through Instagram posts or documentaries. But such information is fragmentary, unsystematised, and reaches pre-service teachers by chance—one participant had been informed "in part" about the production of smartphones but "could not give any details about it anymore" (H1:2, 63)—without being embedded in any frame of knowledge that could guide action.

4.2. The Use Black Box

Even more pronounced than for production is the unknowing that surrounds use. The energy consumption of individual media actions—streaming, cloud use, video-conferencing, social media activity—is opaque to nearly all pre-service teachers, and the material infrastructure that enables each digital act, i.e., data centres, submarine cables, and server farms, remains invisible. One pre-service teacher formulates this epistemic condition precisely (see also H1:1, 27; H1:2, 42; H1:5, 144; H4:1, 405; H4:2, 433; H4:4, 499; H3:1, 307; H2:1, 257; H2:2, 294; H5:1, 615; H5:2, 656; H1:8, 229; H3:3, 365; H4:3, 466):

> *"I personally find it hard, because I know, okay, for everything I do digitally, some big computer has to be standing somewhere processing it. And I know it needs electricity and a lot of energy. But I have no feeling for how much that is. I always feel that I, as a small person, can change things in a lot of areas, but with technology I feel I am really just a very small cog."* (H1:3, 95)

This statement condenses the central paradox of the use black box: knowledge that the problem exists is broadly present; a feeling for its dimensions and magnitude, and any concrete perspective for action, is absent. The image of the "small cog" moreover points to an experience of powerlessness that can undermine individual readiness to act.

Streaming services are known to most pre-service teachers as resource-intensive, yet the knowledge stays superficial and rarely becomes a basis for action. The typical reaction mode is one of postponement: a participant who had learned about streaming capacities "only recently" through a friend concedes that one "could look into that more closely" but that, for now, "that is not important to me at the moment in my everyday life" (H1:5, 150/151). Knowledge enters awareness through peers or chance encounters but is not necessarily converted into behavioural change. The same participant names the structural contradiction in which all users of digital media move: even a life of "a certain asceticism"—staying home rather than going out—does not escape resource-intensive digital consumption, because watching Netflix at home "is still partly environmentally harmful" (H1:5, 136).

The invisibility of digital infrastructures is described by another pre-service teacher with striking vividness: she knows "that there are servers somewhere" and that storage systems "use an incredible amount of electricity," but "how it really works and how much it actually is–that would interest me" (H5:2, 656). She adds a telling illustration:

> *"I said this recently in a group, actually: I had no idea, I don't have it on my radar at all, that when I enter a question–explain the Anthropocene to me–it then accesses an enormous number of sources, and that of course needs a huge amount of electricity and power. And what costs us no energy at all is, for the Earth, simply an enormous energy consumption."* (H5:2, 656)

The passage captures the defining feature of the use black box: the discrepancy between the subjective effortlessness of digital actions and their real resource consumption is so

large that it seems cognitively almost unbridgeable. Another pre-service teacher describes the same mechanism from a generalising perspective, noting that using devices "leaves a footprint somehow", which is something "many people" do not have in mind (H4:1, 420). Pre-service teachers thereby themselves describe the deficit as a collective, societal one.

4.3. Disposal Uncertainty

A particularly pronounced dimension of the black box concerns disposal. Most pre-service teachers report not knowing how digital devices should be properly disposed of or recycled; the few who can name a return route generally cannot say what becomes of the materials afterwards. The result is that discarded devices linger in drawers, cellars, and boxes—not out of indifference but out of practical disorientation (see also H1:1, 17; H1:2, 59; H1:4, 121; H1:5, 147; H1:6, 172; H4:1, 405; H4:4, 510; H3:1, 324; H2:1, 263; H2:2, 294; H5:2, 647; H1:8, 237; H4:7, 601):

> *"Simply because I have no knowledge of it. At my parents' place there are old phones, it is all just lying around. One could take it somewhere so that it is taken apart and the precious metals and things in it are recycled. But basically it just lies around at home, and it tends rather not to get recycled, but then at some point… no idea."* (H1:3, 84)

The specific nature of this knowledge gap is instructive: it is not disinterest but the absence of concrete, easily accessible options for action. One pre-service teacher knows that a box of old devices is waiting in the cellar that ought to be "handed in somewhere" but "honestly does not really know where" (H5:2, 647). For another, data protection concerns block disposal altogether:

> *"I have a lot of dead tech lying around. I know that one can recycle it, and that at the university, for instance, there is a special bin for phones so that they can be recycled. I have handed in only one or two devices there. I would like to recycle further devices too. My only problem is that I still have an old phone with my data on it, and because the screen is broken I have no way to delete all the data, and that stops me from handing it in."* (H1:7, 205)

Data protection and disposal uncertainty together form a double barrier. Devices remain in an intermediate state: neither used nor properly disposed of.

The absence of a societal disposal infrastructure is named explicitly by several pre-service teachers. One observes that awareness "is lacking, also in society," and that although collection points exist, they "are not really talked about," so "many people do not necessarily know where they can hand in their old devices" (H4:1, 405). Another recounts learning, on a zoo visit, that phones can be deposited so that materials are recovered rather than newly mined, and comments that she finds this "important" (H4:4, 510). The example is characteristic: knowledge about recycling infrastructures is acquired through chance experience—a zoo visit, peers, or media content—rather than through systematic information, and even then it does not translate into consistent disposal practice. The lack of any practicable route is felt directly: one participant reports "more or less searching for how I can dispose of these devices at all, so that they might perhaps be recycled" (H1:1, 23).

4.4. Disorientation Regarding Alternatives

A fourth aspect of the black box concerns the lack of knowledge of sustainable alternatives. Unlike food (organic labels, regionality, seasonality), clothing (fair production, second-hand, eco-labels), or mobility (public transport, cycling, rail), digital media technologies offer no established, widely known frames of orientation. The Fairphone is named by several pre-service teachers as the only known sustainable alternative and immediately

qualified as too expensive, delivery times are too long, and its functionality is doubtful. One participant describes the result of this disorientation (see also H1:1, 17; H1:3, 85; H1:5, 142; H4:1, 407; H4:2, 445; H4:4, 495; H3:1, 312; H3:2, 337; H2:1, 257; H5:1, 616):

> *"As for hardware, I would say I can well imagine that sustainable technology exists. But it would really not be at all clear to me where I could even obtain it, apart from refurbished sites. A brand that is established and explicitly produces sustainably is simply unknown to me."* (H1:6, 176)

The disorientation extends beyond hardware to software and digital services. While Ecosia is known to several pre-service teachers as a more sustainable search engine, few can say whether sustainable apps or cloud services exist or how their ecological balance would be assessed. In the domain of software and apps, pre-service teachers lack not only knowledge but the very categories by which more and less sustainable options might be distinguished; one participant suspects that gaming apps and the like "could be a big aspect" but that "many are not aware" of what lies behind them (H1:4, 122). The same participant makes the categorical gap explicit for software: they had "not really" engaged with "whether an app is sustainable or not... in the ecological aspect" (H1:4, 122).

The practical consequence is fragmentary knowledge that cannot serve as a basis for action: a participant has "heard" that downloading rather than continuously streaming videos may reduce server electricity use "or something like that," adds "badly explained, probably," and concludes that she has "never consciously downloaded videos" (H5:2, 649). The structural dilemma is captured especially precisely by another participant:

> *"Especially with streaming, the question is: does one streaming platform need more space than another? Can one compare that? […] If you work your way into it and take the trouble, it is probably less hard, and one can give effective tips. But I have the feeling it is such a very, very large topic that one can get lost in it."* (H1:3, 95)

The image of a "large topic in which one can get lost" is revealing: pre-service teachers sense that sustainable media action would be possible but the complexity of the field and the absence of simple orientation points prevent both the entry into, and the implementation of, such action. The structural dilemma is stated in the form of a question that is more than rhetorical:

> *"I think there is fundamentally a huge knowledge gap in society. And also for me, although I have engaged a lot with sustainability–how one can even use media sustainably at all. I mean, these are really tiny adjusting screws, download instead of stream, which one also really cannot always implement. […] It also raises the question for me: can one even really use media sustainably at all?"* (H2:2, 299)

The question "can one even really use media sustainably?" points to an asymmetry in the participants' accounts: while they can readily name orientation resources for other consumption domains, they can name almost none for digital media technologies. In their own reasoning, the difficulty is therefore not merely one of knowledge but one of available courses of action.

4.5. The Black Box in Contrast: Differentiated Knowledge in Other Domains

The analytical sharpness of the black-box problem emerges from its contrast with the state of knowledge in other domains. The same pre-service teachers who display fundamental knowledge gaps for digital media technologies reason about food, mobility, and clothing in a differentiated way that can guide action. Section 4.5.1 documents that competence in the participants' own accounts; Section 4.5.2 then sets the two sides of the contrast against one another.

4.5.1. Articulated Competence in Established Consumption Domains

Before the contrast is drawn, the competence that the same pre-service teachers display in other consumption domains is documented in their own accounts. Across multiple interviews, their everyday sustainability practices are varied, differentiated, and reflected upon: regional and seasonal shopping, vegetarian or vegan diets, the use of public transport rather than a car, second-hand clothing, and consistent waste separation recur throughout the interviews. What matters analytically is not the intensity of these practices but the fact that they are guided by criteria—provenance, certification, seasonality, production conditions, second-hand acquisition, modal choice—according to which options can be distinguished. One participant sets out several such criteria across domains at once:

> *"We have […] a small plot of land where I grow my own vegetables. […] It is not complete self-sufficiency, but it is something. I make sure that when I buy flowers, they are ones that are friendly to bees. Or now, with my son […], I try to fall back on organic and sustainable products, whether nappies or cosmetics. I try to buy vegetables regionally and seasonally. […] Otherwise, with clothing I also try to buy used things. And when I buy new, then rather brands that are sustainable."* (H3:2, 335)

The passage is not exceptional. Another participant describes an everyday life organised around comparable distinctions, extending across food, clothing, and mobility:

> *"I try to shop regionally anyway and organic where possible. Because I know that this is important for my health, and I try to throw away as little as possible. […] I only ever drink tap water. […] I always turn the light off when I leave the room, and try not to leave my devices charging longer than they need. I actually do not buy clothes very often. […] I cycle a lot."* (H5:2, 645)

The underlying orientation is stated in general terms by another participant, for whom sustainability means "a reflected life in terms of consumption […]: what do I consume, how much do I consume, where does what I consume come from?" (H1:2, 40). That reflection, however, unfolds principally in the domains of food, mobility, and clothing, and is seldom carried over to the participants' own media practices (see also H4:1, 401; H4:2, 435; H3:1, 307; H5:1, 615; H5:2, 644). One participant who is active in environmental protection, eats vegan, and does not own a car states the discrepancy plainly with reference to the sustainability of her media practices: it is, she says, "really an aspect that I do not have in my field of view at all" (H2:2, 284).

Two features of this material bear on the comparison that follows. First, the knowledge at work in these domains is detailed and differentiated rather than fragmentary: participants can say what distinguishes one option from another and why. Second, the categories they apply—origin, production conditions, labelling, durability—are the same categories that Sections 4.1–4.4 find unavailable to them for digital devices and services. Several of the participants quoted here are also quoted or cited in those sections (H1:2, H2:2, H3:2, H5:2), so the comparison can be read within individual cases and not only across the sample.

4.5.2. The Contrast Between the Domains

One participant sums up the contrast:

> *"Topics where I would say I already know very, very well are mobility, nutrition, and also climate change, CO_2 cycles. There I already know quite a lot, I would say. And now, for instance, the things about media use–there I still know very, very little, and I only stumbled onto it through [the study]."* (H2:2, 286)

In the participants' accounts, the difference does not present itself as one of motivation: they describe themselves as interested, but name orientation resources only for the established

domains. In domains such as food or clothing, participants refer to an infrastructure of labelling systems, public discourse, media reporting, and social norms that enables and supports sustainability knowledge. Even these better-charted domains, to be sure, rest on externalised "imperial" costs that remain only partially visible to consumers [30]: the point is not that food or clothing are wholly transparent, but that they are at least furnished with orientation repertoires that, in the participants' accounts, are scarcely available for the digital domain, where only Fairphone and Ecosia are named, and with reservations. For digital media technologies participants name no such infrastructure; knowledge enters awareness—if at all—through peers, chance reception of social media posts, or isolated prompts in seminars rather than through systematic channels (see also H1:1, 17; H1:2, 40; H1:3, 95; H4:1, 405; H4:4, 512; H3:2, 350; H5:1, 629; H5:2, 660; H3:3, 379). Table 3 sets out this contrast.

Table 3. The within-subject contrast between established consumption domains and digital media technologies across four orientation resources and the resulting pre-service teacher stance, as articulated by the participants. The entries describe the orientation resources participants were able to name; they are not an assessment of the domains themselves. Left-hand column: Section 4.5.1; right-hand column: Sections 4.1–4.4.

Orientation Resource	Food, Mobility, Clothing	Digital Media Technologies
Labelling/certification	Readily named (organic, fair-trade, eco-labels; regionality)	Largely unknown to participants (only Fairphone and Ecosia named, and qualified)
Public and media discourse	Perceived as sustained and visible	Perceived as weak; knowledge arrives by chance
Social norms	Experienced as present and as guiding action	Not perceived as formed
Established alternatives	Multiple and readily named	Few named, qualified, and hard to locate
Resulting stance	**Differentiated knowledge that can guide action**	**Upstream knowledge and perception deficit (the black box)**

A pre-service teacher who describes herself as "very strongly interested in sustainability" and reports numerous sustainable everyday practices nonetheless articulates the failure at the interface of interest and knowledge: "I find we simply know far too little about it. So I now see that this is an area one has not dealt with at all" (H4:5, 539). Her closing self-assessment is unsparing:

> *"Basically I am sorry that I could not say too much about it, because I simply notice that I have engaged with it far too little, even though I would claim that I actually use digital media a great deal and am very tech-savvy, and am also very strongly interested in sustainability. But there is simply too little knowledge yet, and, overall, much more need for explanation."* (H4:5, 542)

This self-description shows that motivation for reflection is present both in relation to digital media and in relation to sustainability—but that the two do not meet in the field of sustainability-related media practices. Another pre-service teacher generalises the finding to society at large, observing that people attend much more to sustainability "with food, with clothes, when shopping, with waste separation" than "at their desk, in front of their computer," not because they refuse to engage but because the digital "is so included in everyday life" that sustainability "with media is not yet so present" (H4:2, 456).

Taken together, these accounts suggest that the pattern cannot be accounted for by the individual knowledge gaps of particular students: it recurs across multiple interviews and is specific to the digital domain. The comparison drawn here is a qualitative, within-subject comparison of what participants were able to articulate in the interview; it does not measure knowledge or behaviour, and it establishes no prevalence.

4.6. Deviant and Contrasting Cases

The pattern described so far is not without exceptions, and the exceptions are instructive because they specify the conditions under which the black box narrows and, in one respect, qualify the account given above. Four groups of cases depart from the pattern.

A first and substantial group consists of participants who do maintain practices that reduce the material footprint of their media use, without describing them as sustainability practices. The most frequently reported is the deliberate extension of a device's life. Participants describe using smartphones, laptops, and tablets until they cease to function:

> *"I am currently using a phone that is more than eight years old. […] Where technology is concerned, I really use it until it is genuinely broken."* (H1:6, 165)

The same orientation appears as a refusal of the manufacturers' release cycle—"not buying a new iPhone just because the new iPhone is on the market, but really using it until it truly cannot go on" (H3:3, 362)—and it recurs across multiple interviews (see also H1:2, 42; H1:3, 85; H1:4, 108; H4:2, 437; H4:5, 526; H3:2, 339; H5:2, 647). Related practices are reported with comparable frequency: repair is considered before replacement (H1:2, 53; H4:7, 595; H3:2, 345; see also H1:1, 16; H1:3, 94; H4:1, 410; H4:5, 534; H5:1, 624); devices are bought used or refurbished (H1:7, 197; H3:2, 337; H5:2, 647); and several participants acquire only what they take to be necessary, declining a tablet or a second screen where a multi-function device suffices (H1:6, 167; H2:2, 289; H1:4, 111).

What is decisive for the argument of this article is the reason these participants give. Where a reason is given, it is characteristically financial, functional, or habitual rather than ecological; sustainability appears as a by-product rather than as a decision (see also H1:2, 43; H1:3, 88; H3:2, 337; H4:5, 518). One participant states both motives in the same breath and puts the financial one first:

> *"Well, I try–my laptop, for instance, was bought used. My phone is used. There I try, partly out of stinginess, because in part I do not see why I should spend that much money on it […]. If it is possible for me to buy it used, I buy used rather than new."* (H3:2, 337)

These cases are therefore not counter-examples to the black box but a further specification of it. The practices exist; what is absent is the knowledge that would allow the participants to recognise them as sustainability practices, to assess their effect, or to extend them deliberately. The opacity concerns the reasons rather than the behaviour.

A second group does state a sustainability motive, and these cases show where such a motive attaches and where it loses its footing. It attaches to what is visible and countable. The shift from paper to digital media is the clearest instance: one participant justifies acquiring a tablet explicitly in these terms, saving paper "for which trees die", and then immediately articulates the conflict this creates with the electricity and the production of the device itself, without being able to resolve it (H3:3, 365; see also H1:1, 16; H1:4, 113; H1:7, 197; H4:1, 402; H4:2, 454; H1:6, 165). Another participant sets the rejection of cookies against the saving of paper in the same movement of thought (H3:2, 336). Downloading in place of streaming is described by one participant as having "practical as well as sustainable aspects" (H1:6, 170; see also H1:2, 42; H1:3, 85; H4:1, 402; H5:2, 647), and one participant reports buying a refurbished laptop on explicitly ecological grounds (H5:2, 647). In each case, the motive fastens onto a tangible referent—a sheet of paper, a second-hand device—and becomes indeterminate where the referent is an infrastructure. In these cases, sustainability motivation is present but finds no point of application where the referent is an infrastructure.

A third group departs from the individualising frame described in Section 5.3, and does so at precisely the points where a structural barrier is physically encountered. Several

participants name the design of devices as the obstacle rather than their own behaviour: batteries that can no longer be exchanged, repairs that can only be carried out in authorised shops, and the calculation that this forces on the user.

> *"If you look back a few years, phones were always made so that you could open the back and change the battery. And in recent years hardly any phone is built so that you could change anything yourself as a user."* (H4:1, 411)

One participant explicitly defers a purchase in the expectation that replaceable batteries will return (H1:5, 152), and another wishes for a stronger obligation on companies, expressing discomfort at shifting responsibility onto the end consumer (H5:1, 631; see also H1:2, 53; H1:6, 172; H4:5, 534; H2:1, 261). The individualising frame is therefore dominant but not total: where the structural condition takes a material form that can be encountered in use, it is named as structural. Where it does not—as with supply chains, data-centre energy, or disposal infrastructures—it is not.

A fourth and much smaller group possesses concrete knowledge of a route of disposal, and in each case that knowledge derives from an encounter with a visible facility rather than from information in the abstract. One participant describes bringing devices to a collection point as a matter of course and checking where they can be handed in (H3:3, 384/385; see also H4:3, 479). Another knows the collection container for mobile phones at her university and has already used it, and is prevented from handing in the remaining devices only by an unresolved data protection problem (H1:7, 205). Even these participants, however, report little knowledge of what becomes of the materials afterwards, so that the distinction drawn in Section 4.3 holds within this group as well: what is missing is not the return point but the onward route (see also H1:3, 94; H1:5, 140; H3:1, 307; H5:2, 647).

One further observation runs through all four groups and deserves emphasis because it is a negative one. The sources to which participants attribute their orientation are peers—"friends who kept their devices longer or bought them recycled [...] and I started to rethink my own consumption" (H1:1, 22; see also H1:2, 50; H1:3, 91; H1:4, 104; H4:2, 449; H3:1, 309; H5:2, 644)—together with family, media content, and institutional facilities. Institutional provision is named as shaping media practices in both directions: library devices and campus licences reduce the pressure to acquire, while specific hardware and software requirements create it (cf. H1:2, 48; H1:3, 72; H1:4, 108; H1:8, 238; H4:1, 399; H3:1, 327; H3:2, 340). University teacher education is named as a source of knowledge about the socio-ecological dimensions of digital media technologies in none of the cases reported here. This is consistent, from the side of the deviant cases, with what participants state explicitly (Section 5.2).

Read together, the four groups suggest that what varies across cases is less the disposition of the person than two properties of the object. The first is the visibility of a concrete option: a collection container in a university building, a repair shop, a second-hand market. The second is the availability of a tangible referent against which an effect can be estimated: a sheet of paper, a battery, a price. Where both are present, practices form and can be given reasons. Where neither is—as with the energy of a query, the provenance of a component, or the fate of a discarded device—neither a general sustainability orientation nor an explicit ecological motive produces them. This bears directly on the implications developed in Section 5.4: the conditions under which these pre-service teachers did come to know and to act are conditions of visibility and measurability, not of exhortation.

5. Discussion

The findings, taken together, support a single overarching claim, which this section develops through several lenses before translating it into implications: the socio-ecological

black box of digital media technologies cannot be explained as an individual knowledge deficit, and is read here as a structurally produced condition which, according to the participants' accounts, their teacher education has so far left largely unaddressed. This section first characterises the awareness–practice gap and the structural interpretation advanced for it (Section 5.1), then considers two contexts that may contribute to it—teacher education as described by the participants (Section 5.2) and the individualisation of structural problems (Section 5.3)—before drawing out implications for teacher education and ESD (Section 5.4) and noting the study's limitations (Section 5.5).

5.1. The Awareness–Practice Gap as the Central Finding

To begin, the opacity of digital media technologies is differentiated. Reading the four dimensions through Shove and colleagues' model [24], the black box is not the uniform absence of knowledge but a patterned gap in the competence element of otherwise well-equipped practices. Pre-service teachers are highly competent operators of devices and services—the materials and meanings of their media practices are fully in place—yet the sustainability-relevant competence is missing at each of four points: they can scarcely evaluate production, sense the magnitude of use, locate disposal options, or recognise alternatives. Crucially, these are not four separate deficits but a single condition refracted through the phases of a device's life. This has a practical upshot: because the gap is located in competence rather than in materials or meanings, it is in principle addressable through education—provided the education targets infrastructural literacy rather than mere exhortation.

More fundamentally, the findings point beyond the individual level. A distinction should, however, be drawn at the outset between the empirical finding and its interpretation. What the interviews establish is a domain-specific asymmetry in what participants are able to articulate, one that is not adequately explained by individual disinterest or by a general lack of sustainability knowledge. The mechanisms invoked to account for that asymmetry—externalisation, the weakness of public and regulatory discourse, the commercial interest in seamlessness—are not themselves objects of this study: no data were collected on manufacturers, regulation, or supply chains. They are advanced as a theoretically grounded interpretation that the findings support without demonstrating, and the argument is stated according to that strength throughout. The within-subject contrast in Section 4.5 provides the central empirical basis for this reading. The same pre-service teachers who, for a smartphone, can name, at most, proxies such as durability or price, and rarely an ecological criterion, reason fluently about food miles, fair fashion, and modal choice. Since the same persons reason across all domains, the difference cannot be explained by stable individual dispositions alone and is more plausibly attributed to domain-specific conditions—specifically, to the presence or absence of a supporting infrastructure of sustainability-related labels, discourse, reporting, and norms. This is consistent with the account of digital capitalist externalisation developed in Section 2.5 [27,29,30], according to which the invisibility is produced and maintained by structures that have an interest in, or are simply indifferent to, keeping the material substrate of the digital out of view. According to this interpretation, the invisibility of digital infrastructures is not accidental but is sustained by insufficient public and, above all, critical discourse about the unsustainability of digital media technologies, by missing political regulation, and by economic practices that, along digital capitalist lines, externalise socio-ecological impacts. In practice theoretical terms, the pre-service teachers' thoroughly domesticated media practices can be read as the kind of everyday routine through which, on Brand and Wissen's account, the imperial mode of living is unconsciously reproduced—the device is used, upgraded, and discarded without its planetary conditions ever entering the field of action.

The recurring experience of the "small cog" and the resigned acceptance of the status quo can be understood as the subjective correlates of this structure. Interventions that treat the problem as one of individual awareness are therefore likely to be necessary but insufficient; they address the symptom while the structure may regenerate the opacity.

This structural reading can be sharpened by relating it to the well-documented attitude–behaviour gap—the observation that pro-environmental attitudes and values are not translated consistently into everyday practice [43,44]. In the domains of food, mobility, and clothing, that gap typically opens between existing knowledge and competing motives such as convenience, cost, and social norms. In the domain of digital media technologies, the data reveal a gap of a different and prior quality: for most pre-service teachers, the very knowledge base on which such a tension could form is missing. What emerges is therefore not, in the first instance, a deficit of motivation or will but an upstream deficit of knowledge and perception, produced by the invisibility of digital media technologies, their infrastructures, and above all their socio-ecological consequences—the black box that systematically undercuts individual reflection.

Read through practice theory [15,17], this deficit can be understood as a result of how media practices are embedded in individual routines, social norms, and institutional demand structures that make sustainability-oriented alternatives difficult to form. Digital devices are woven into pre-service teachers' everyday lives as self-evident infrastructure, yet their socio-ecological dimension does not belong to the everyday stock of knowledge on which routines are built [17], and so the preconditions for criteria-guided, informed development of sustainability-related or consumer-critical media practices are absent [26]. The experience that several pre-service teachers report, of having no effective options for action, is not merely a subjective distortion. It plausibly corresponds to a socially produced opacity: according to the interpretation advanced here, manufacturers have no compelling interest in making socio-ecological downstream costs visible, public information structures around sustainable production, use, and disposal are weakly developed, and, judging by the participants' accounts, teacher education has so far rarely addressed the intersection of digital media and sustainability.

This same logic can account for the involuntary accumulation of devices reported in Section 4.3, which mirrors a finding of Kannengießer's work: where consumer-critical media practices are supported and legible, they issue in deliberate waste avoidance, whereas their foreclosure leaves the same underlying orientation to produce an involuntary accumulation of dead devices [25,26]. The difference between the two outcomes appears to lie less in the disposition of the person than in the availability of a practicable pathway: sustainability-related media practices are enabled or foreclosed at the level of infrastructure and practice, not merely of attitude.

The comparison with Kannengießer's work is instructive in a second respect: where explicit consumer-critical media practices do emerge—around repair cafés, Fairphone use, or sustainability-oriented online communities—specific knowledge about production, use, and disposal meets a supportive social infrastructure and collectively shared frames of interpretation; both are largely absent for the pre-service teachers of this study [26]. The finding also confirms a broader point: sustainability-oriented action in one domain does not immunise against unreflected behaviour in another; ambivalence is the rule rather than the exception [26]. The asymmetry between pre-service teachers' competent general sustainability practices and their less reflected media practices is thus better read as the expression of a specific, societally located deficit of knowledge and infrastructure in the digital domain than as a sign of personal inconsistency.

5.2. Teacher Education as Described by the Participants

Beyond the everyday register, the participants' accounts point to a gap in their teacher education at the intersection of ESD and media education. Across the interviews, pre-service teachers report that their university teacher education supplied neither theoretical knowledge nor pedagogical concepts for connecting digital media technologies with (un)sustainability or, more broadly, for relating the two educational programmes of media education and ESD to one another. As the participants describe it, this gap has consequences for their agency in their private lives and, potentially, for their future professional practice in the classroom. The same lack of provision, and a corresponding wish for relevant courses, recurs across the interviews (cf. H1:8, 242; H3:3, 389; H4:3, 462; H4:7, 603).

The point matters because teacher education is itself a practice-forming context. It supplies the stocks of knowledge, interpretive frames, and repertoires of action that teachers later carry into their own teaching; and practices, as practice theory stresses, do not arise spontaneously but through social learning in settings that mark them as normal, meaningful, and feasible [15,17]. If the ESD–media education intersection does not appear as a relevant field in teacher education, future teachers may be less likely to address it systematically at school. A curriculum's silence on a topic is, in this light, not necessarily a neutral omission; it may contribute to reproducing the status quo.

This is all the more striking because the pre-service teachers describe themselves not as disinterested but as eager for information, and several explicitly wish for relevant courses. One makes the point while reflecting on the interview itself:

> *"I think you have probably noticed that with many questions I first have to stop and think. […] But this really is a subject area that–well, sustainability does play a role, but as for media, their acquisition, use, and disposal, one has simply never given it any thought."* (H4:6, 567)

Another frames the need as a societal one:

> *"I myself still need a bit more input here, because I never quite know how a laptop is made, what all goes into it. I think it is important for society to call this information clearly to mind, so that one recognises why one should do something–and so that it might also be easier to put into practice."* (H4:4, 512)

A third simply registers the theme's absence from their studies:

> *"Media in combination with sustainability […] was not addressed at all over the course of my studies."* (H5:2, 659)

These self-diagnoses are educationally significant: they signal a genuine openness to acquiring knowledge about digital media technologies and (un)sustainability that, in their experience, has so far met no corresponding educational provision. The implication is a demand for the systematic linking of the two educational fields—a demand taken up in Section 5.4.

5.3. The Individualisation of Structural Problems

A final strand concerns how sustainability is framed. In the pre-service teachers' discourse, it appears almost exclusively as a matter of personal responsibility and individual consumer choice—which device to buy, how long to keep it, which content to use or avoid. Demands for structural change—legal regulation, action against planned obsolescence, corporate responsibility for supply chain transparency, or manufacturer liability for disposal costs—surface in only a handful of interviews.

This individualisation of environmental responsibility is well documented. Maniates showed how, in liberal consumer societies, ecological responsibility is systematically displaced onto individual consumers—an "individualisation" that pushes the structural causes of environmental problems out of public discourse [45]. The pre-service teachers of this study reproduce the pattern: they devise individual strategies such as prolonging a device's life or seeking repair, without extending their critique to the structural conditions that make these strategies necessary and simultaneously obstruct them—deliberately impaired repairability, or the missing infrastructure for disposal and recycling.

The individualising frame is not, however, wholly uncontested. A few participants break with it, pointing to the limits of individual action and to the question of responsibility:

> *"If only there were a greater obligation for companies, too, to place the focus on sustainability themselves. I always find it a bit difficult to shift it all onto the end consumer."* (H5:1, 631)

Such voices matter for ESD. An approach oriented to *Gestaltungskompetenz*—the competence to shape a sustainable future—must reach beyond equipping learners for individual consumer decisions and open up the political dimensions of action as well: questions of societal regulation, collective action, and structural change belong to the subject matter as much as the reflection on individual media practices. This is especially so for digital media technologies, where the complexity of global supply chains and the invisibility of global infrastructures confine individual choice to narrow limits in any case.

5.4. Implications for Teacher Education and Education for Sustainable Development

Three implications for teacher education follow. (i) Infrastructural literacy should be an explicit objective. Pre-service teachers need not become supply chain experts, but they do need the categories—embodied energy, life-cycle thinking, e-waste flows, repairability—that make the material substrate of the digital perceivable and discussable. Without such categories, as the software case shows, participants cannot even formulate the questions. (ii) The digital should be treated as an object of sustainability education and not only as a medium. The very devices used to teach about sustainability carry a footprint that can itself become curriculum content, turning the classroom's own technology into an object lesson. (iii) If the deficit is, as argued here, structurally produced, media education here should be critical in the strong sense: it should make the production of invisibility—externalisation, weak regulation, commercial seamlessness—itself an object of analysis, connecting individual practice to the political economy of digital capitalism. This is where media education's traditional attention to institutional and economic conditions can most productively meet ESD's competence orientation [32–34].

5.5. Limitations and Future Research

Several limitations qualify these claims: This study is qualitative and exploratory; its purpose is to reconstruct patterns of meaning and practice, not to establish their prevalence in a representative population. The sample consists of pre-service teachers at a small number of sites, which is appropriate to the research question—precisely because this group represents future multipliers—but limits transferability to other populations. Interview accounts capture reported rather than observed practice, and the translation of excerpts from German, though careful, inevitably involves interpretive choices. Finally, the analysis reconstructs the socio-ecological black box of digital media technologies at a particular moment; the rapid evolution of both the technologies and the surrounding discourse means that the specific contours of the opacity may shift, even as the conditions that, according the interpretation advanced here, produce it may persist. Future research could

combine this interpretive account with observational or infrastructural methods, extend the sample beyond teacher education, and test whether targeted interventions in infrastructural literacy measurably alter sustainability-related media practices. Three further limitations follow from the design. First, the comparison domains of food, mobility, and clothing were not addressed by specific questions but raised by participants in response to an open question, and were explored less densely than the digital domain. The material documenting articulated competence in those domains is correspondingly thinner. The within-subject comparison should therefore be read as a comparison of what participants articulated in the interview, not of what they know or do. Second, data collection extended from December 2022 to May 2025 and thus spans the period in which generative artificial intelligence entered public discourse, a development that the interviews themselves address. Two interviews were conducted in December 2022, in the first weeks after the public release of ChatGPT (OpenAI, San Francisco, CA, USA); the remaining twenty-one followed between 2023 and May 2025. The collection thus spans the period in which the use of generative AI and the public debate about it, including its energy demand, expanded. Articulacy was assessed by whether, and how specifically, participants addressed each of the four dimensions in the coded segments. Read in chronological order, the interviews give no indication of a change in the articulacy of socio-ecological reasoning: the four dimensions of opacity are present across the whole collection period, including the interviews conducted in 2025. This is an observation rather than a comparison in the strict sense. It is consistent with the structural reading advanced in Section 5.1, but a qualitative design of this kind cannot establish the inference. Third, the analysis was designed, conducted, and coded by a single researcher, with the consequences set out in Section 3.4.

6. Conclusions

Digital media technologies are, for the pre-service teachers in this study, an invisible sustainability issue. Their socio-ecological dimensions—production, use, disposal, and the space of alternatives—constitute a differentiated black box that the same pre-service teachers do not encounter in the domains of food, mobility, or clothing. The contrast between these domains indicates that the opacity cannot be explained as an individual failing; read through accounts of the externalising logic of digital capitalism, weak public and critical discourse, and missing regulation, it appears as a structurally produced blind spot.

For Education for Sustainable Development and media education, this diagnosis is also a mandate. If prospective teachers cannot perceive the material substrate of the digital, they cannot make it perceivable for their students, and the blind spot is likely to be reproduced across generations. Opening the black box therefore requires more than information: it requires an infrastructural literacy that treats digital technology as an object of sustainability concern, connects individual media practices to their political–economic conditions, and equips future teachers to render the invisible discussable. In a world in which teaching and learning are ever more thoroughly digital, making the sustainability of the digital itself teachable is not a peripheral task but a central one for the 2030 Agenda's convergence of quality education, responsible consumption, and climate action.

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Institutional Review Board Statement: Ethical review and approval were waived for this study by Ludwigsburg University of Education, since participants were adults; no minors or other vulnerable groups were involved. Participation was voluntary. Participants were recruited via lecturers and informed in advance that declining to take part would entail no disadvantage and that they could end the interview at any time without giving reasons.

Informed Consent Statement: Consent was given verbally at the start of each interview, after participants had been informed about the purpose of the research, the voluntary nature of participation, the right to withdraw at any time, the recording and anonymisation procedure, and the deletion of the audio file after transcription; it is documented in the anonymised transcripts.

Data Availability Statement: The data presented in this study, and the interview guide, are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

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Appendix A

The interviews were coded in line with Grounded Theory [40] using ATLAS.ti; the full category system comprises seven superordinate categories (Section 3.3). The socio-ecological black box is a cross-cutting theme that draws principally on the category of sustainability-related media practices (acquisition, use, disposal) and on the contrast with general sustainability practices. Figure A1 gives an overview; Table A1 lists the relevant open codes, grouped by the four black-box dimensions together with the cross-cutting and contrast categories.

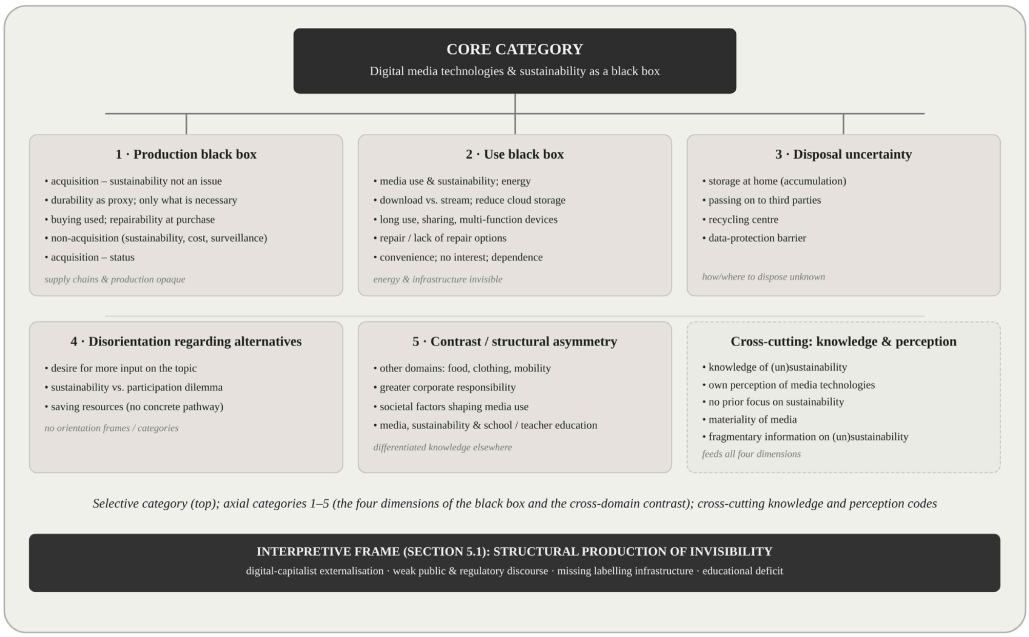


Figure A1. An overview of the black-box code tree: the core (selective) category, the five axial categories (the four dimensions of the black box and the cross-domain contrast), and cross-cutting knowledge and perception codes, set against the interpretive frame of the structural conditions through which, according to the reading advanced in Section 5.1, the invisibility is produced. Codes are translated from the German ATLAS.ti code list; the coding procedure follows Grounded Theory [40,41]. The interpretive frame is not part of the code tree. The selection of codes is illustrative, not exhaustive.

Table A1. The code tree for the black-box theme (open codes, grouped by category). Open codes that bear on more than one category are listed under each.

Open Code
Core category (selective coding)
Digital media technologies and sustainability as a black box
Cross-cutting: knowledge and perception
Knowledge of (un)sustainability
Own perception of digital media technologies
No prior focus on sustainability in digital media technologies
Materiality of media
Fragmentary information on the (un)sustainability of digital media technologies
Desire for more input on the topic
1 · Production black box (acquisition)
Device acquisition—sustainability
Acquisition of digital technologies—sustainability not an issue
New device acquisition—stable functionality (durability as proxy)
Acquisition—only what is necessary
Acquisition—status
Device acquisition—repairability
Buying used devices
Non-acquisition for sustainability reasons
Non-acquisition—big data, surveillance
Non-acquisition—financial reasons
Non-acquisition—no interest
2 · Use black box
Own media use and sustainability
Media use—download instead of stream
Reducing cloud storage
Long device use duration
Sharing devices/media
Living situation and media use (incl. sharing)
Individual (non-shared) device use
Multi-function devices
Repair of digital media technologies
Lack of repair options
Low media use
Media use—convenience
Media use—no interest
Media use—abstaining for data protection reasons
Digital media as a source of information on sustainability
Dependence of everyday activities on devices
Energy (ecological dimension of use)
Digital instead of paper
Non-sustainable practices
No abstention from digital media technologies for sustainability reasons
3 · Disposal uncertainty
Disposal—storage at home (involuntary accumulation)
Disposal—passing on to third parties
Disposal—recycling centre
Disposal—data protection barrier
4 · Disorientation regarding alternatives
Sustainability of media vs. participation through media (structural dilemma)
Saving resources (aspiration without a concrete pathway)
Desire for more input on the topic

Table A1. *Cont.*

Open Code
5 · The black box in contrast (structural asymmetry)
Food
Clothing
Mobility
Waste (especially plastic)
Consumption
Low consumption
Sustainable lifestyle
Water
Energy (also listed under category 2)
Greater corporate responsibility (critique of individualisation)
Societal factors shaping media use
Digital media, sustainability, school
Digital media, sustainability, teacher education
Higher education as a factor in device acquisition
School as a factor in device acquisition and use

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