Journal of Biosocial Science (2025), page 1 of 19
doi:10.1017/S0021932025000227

CAMBRIDGE UNIVERSITY PRESS

RESEARCH ARTICLE

Unravelling biosocial dynamics? The placenta as a postgenomic bio-object in environmental epigenetic research on air pollution

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(Received 10 January 2024; revised 1 June 2024; accepted 17 December 2024)

Abstract
Air pollution exposure and its health effects are a central concern of environmental epigenetic research with birth cohorts. This article explores why researchers have turned to the placenta as a research object to study the dynamic interactions between in utero exposure to air pollution and future child health. Drawing on Science and Technology Studies, particularly the bio-object concept, this article analyses the transformation of the placenta into a technologically manipulated postgenomic bio-object through scientific discourse and practice. Building on ethnographic fieldwork conducted at an institute of epidemiology and public health in Spain, we analyse how researchers deal with the tension between the placenta's promises for epigenetic research and the practical research realities in postgenomic sciences. First, researchers discursively call upon the placenta as a suitable research object that embodies air pollution exposure and becomes entangled with and responds to this exposure via epigenetic changes. Studying the placenta promises to elucidate the temporally dynamic and environmentally embedded process of disease development as one of postgenomics' core epistemic concerns. Second, in practice, however, accessing and preparing the postpartum placenta for epigenetic analysis defies its promise as a postgenomic bio-object. The constraints of research with birth cohorts, such as only having access to the postpartum placenta at birth, limit what researchers can know about the dynamic process of disease development. Third, we show how researchers deal with these limitations by assembling additional data in and around this organ to recontextualise the epigenetic analysis performed in the postpartum placenta and revive its postgenomic character. We conclude by discussing how ethnographies of epistemic practices provide entry points to collaboratively reflect upon the theoretical and methodological opportunities and challenges in birth cohort research to study biosocial dynamics. We suggest avenues for using qualitative social science perspectives for future biosocial research and collaboration between the social and life sciences.

Keywords: Environmental epigenetics; postgenomics; placenta; air pollution; biosocial dynamics; birth cohorts; bio-object

Introduction

Current public and scientific discourse frames air pollution as a major environmental challenge humans and non-humans face alongside climate change. According to the World Health Organization (2022), air pollution is linked to 6.7 million premature deaths each year worldwide and poses a significant risk for respiratory and cardiovascular diseases. At the same time, the

disease burden is unequally distributed within populations. For example, groups with lower socio-economic status tend to be exposed to higher levels of air pollution, and particularly children have been found to be more susceptible to exposure (European Environment Agency 2023). Understanding the underlying biological mechanism of such effects has become a central goal for environmental health sciences.

In recent years, life scientists have started investigating environmental epigenetics as a potential mechanism for mediating air pollution's health effects. Environmental epigenetics is considered one of the paradigmatic postgenomic sciences that explores how socio-material environments, such as toxicants, stress, or nutrition, induce biochemical and structural changes on DNA that impact gene expression without changing the genetic code itself (Allis *et al.* 2007). One of the most commonly studied epigenetic mechanisms is DNA methylation (a process by which methyl groups add to DNA molecules), followed by histone modifications and RNA modifications. In contrast to permanent changes in DNA (for example, gene mutations), epigenetic changes are not fixed but allow us to understand bodies as dynamically shaped by the environments in which they live. Epigenetic research advances an understanding of toxicants' health effects as biosocial phenomena unfolding across time (Meloni *et al.* 2022; Rossmann and Müller 2024); that is how the social, including toxic exposures, becomes biological over the life course (Blane *et al.* 2013).

To investigate such biosocial phenomena, longitudinal birth cohorts have become influential 'technologies of evidence' (Gibbon and Pentecost 2019) for environmental epigenetic research. Cohort studies collect clinical, physiological, molecular, exposure and lifestyle data at several points in participants' lives and associate them with disease outcomes. Epigenetic research with cohorts currently concentrates on exposures during early developmental periods, particularly prenatal periods, and their impact on future adults and the next generations (Gibbon and Lamoreaux 2021). This emphasis on pregnancy puts into focus research materials collected in cohorts capable of embodying such exposures during pregnancy, such as the placenta (Lappé and Hein 2022).

Science and Technology Studies (STS) and related fields are beginning to examine ethnographically how birth cohorts shape environmental epigenetic knowledge production in practice (Penkler 2022; Pinel 2020). Contributing to this unfolding scholarship, the paper focuses on the placenta, with which scientists have become fascinated in epigenetic research to elucidate the link between prenatal environmental exposures and later life diseases. Although the placenta is a central organ for foetal development, biomedical literature argues that it has been understudied (Guttmacher *et al.* 2014; Pasca and Penn 2010). In clinical settings, it was long regarded as waste after birth (Waldby and Mitchell 2006). The growing relevance of the placenta in epidemiological studies reflects a broader development in birth cohort studies since the 1990s to include biological materials in routine data collection alongside survey data and medical records. Fannin and Kent (2015) discuss placenta collection as part of the increasing attention to pregnancy as 'an important "origin point" for understanding a child's future health'. While collecting placentas has been primarily tied to the potentiality of this material to become valuable in the future if new techniques and methods arise to analyse them, epigenetic research comes with the promise to redeem such hopes for epidemiological studies (Fannin and Kent 2015; Lappé and Hein 2020). As STS scholars, we ask: How do scientists transform the placenta into a suitable research object to study the dynamic health effects of air pollution exposure in epigenetic research? What are the opportunities and challenges regarding the epistemic potentials ascribed to this organ and the practical research realities that scientists encounter in birth cohort research?

To approach these questions, we pair social science literature on postgenomics with the concept of bio-objects (Vermeulen *et al.* 2012; see section *Postgenomics, cohort studies, and bio-objects*). We will develop the concept of the postgenomic bio-object to analyse the discourse and practices we observed and to better understand the role the placenta plays in epigenetic research on air pollution exposure. Drawing on ethnographic fieldwork at an institute for epidemiology and public health in Spain, we trace the transformation of the placenta into a suitable research object

https://doi.org/10.1017/S0021932025000227 Published online by Cambridge University Press

from the viewpoint of epigenetic research. In particular, we show how our interlocutors first discursively discuss the placenta as an organ that encloses information on air pollution exposure and dynamically becomes associated with and responds to this exposure via epigenetic changes. Second, we detail how the research realities in birth cohort studies defy its postgenomic promise, such as only having access to the postpartum placenta after birth. Third, we demonstrate how researchers deal with these limitations by assembling additional data connected to this organ to revive its postgenomic character. By analysing the practices of conducting epigenetic research on air pollution exposure in the placenta, we offer ethnographically thick accounts of where, when, and how researchers stabilise the biosocial dynamics of lived experiences. We close by discussing the methodological potential that arises from ethnographies of epistemic practices to reflect upon the methodological opportunities and challenges of birth cohort research. We suggest potential avenues for future biosocial research and collaboration between the social and life sciences, including reflections on mixed methods approaches.

Postgenomics, cohort studies, and bio-objects

The postgenomic turn in environmental health sciences

Capturing the biosocial dynamics of lived experiences and their health effects has become a key concern of postgenomics. Social science scholars refer to postgenomics as a period and an intellectual programme beginning after the sequencing of the human genome in 2001 and, thus, the conclusion of the Human Genome Project (HGP) (Meloni 2016; Richardson and Stevens 2015). Initially, the HGP aimed to find genetic explanations for common diseases and susceptibilities. However, these expectations have only been partially met. Instead, as Fox Keller (2015) outlines, the HGP's findings shifted conceptualisations of the genome from a stable blueprint of life towards 'a dynamic and reactive system' responding to its environment.

Conceptualising the genome as responsive to its environment contrasts with the reductionist, individualistic, and skin-bounded visions of bodies offered by twentieth-century biology (Fox Keller 2000). Instead, STS scholars argue how postgenomics embraces theories of relationality that emphasise the dynamic interactions between genomes and their surrounding environments (Gibbon *et al.* 2018). These works particularly point to environmental epigenetics' role in redeeming these promises, offering a biological mechanism to show how environmental factors such as toxicants impact gene expression and, ultimately, disease aetiology (Müller *et al.* 2017; Rossmann and Müller 2024).

We want to highlight two characteristics of postgenomics that social science literature discusses in the context of environmental epigenetics. The first is epigenetics' emphasis on relationality. Scientists increasingly conceptualise environments, bodies, and their genes not as discrete entities but as entangled with their spatial and temporal contexts that permeate each other on the molecular level (Meloni 2018). Niewöhner (2011) argues that, in theory, these complex renderings of environment/human relations could promote visions of health and disease that recognise organisms as embedded in and dynamically shaped by their past and surrounding environments. Second, social science literature shows how postgenomics emphasises the developmental plasticity of bodies and their genomes across novel temporal horizons (preconception, prenatal periods, infancy, childhood, adolescence, adulthood, and generations) (Lappé and Landecker 2015; Meloni 2018). While postgenomic sciences promote a life course perspective, prenatal periods, so-called 'critical windows of development', currently receive the most attention in environmental epigenetic research (Mansfield 2017).

To track these long-term and latent effects, social science scholars argue that longitudinal birth cohorts have become a key technology in postgenomic research designs (Gibbon and Pentecost 2019; Lamoreaux 2020; 2023; Lappé and Hein 2020). These studies increasingly integrate epigenetic data to make exposure and outcome relationships evident. Gibbon and Pentecost

https://doi.org/10.1017/S0021932025000227 Published online by Cambridge University Press

(2019) highlight the rising relevance of longitudinal birth cohorts for biosocial research to understand 'how biological, social and environmental processes interact over time and contribute to health inequalities.' Lamoreaux (2023) suggests how they have become a 'contextualizing force' to place individual health conditions in the broader context from which they emerge. Lappé and Hein (2020) argue that in placental epigenetic research, longitudinal birth cohort studies have become a pivotal tool for reaffirming claims about the persistent effects of prenatal exposures by relating them to other health data collected over time. Our research substantiates what STS research on placenta epigenetics has argued, namely that the placenta discussed 'as an agential and relational organ' renegotiates how embodiment is imagined (Lappé and Hein 2022). Lappé and Hein (2022) point to the specific temporal logics of the placenta as an organ that embodies evidence of past in utero exposures and provides clues about future child health. Contributing to this unfolding scholarship, we further learn how researchers negotiate these discursive promises amid practical research realities. We will specifically focus on the strategies researchers develop to produce temporal connections between exposures, development, and associated health outcomes in relation to the placenta and epigenetic research as a novel contribution.

The placenta as a bio-object

To discuss the placenta's role as a research object, we will look at the placenta as a bio-object. At its core, the bio-object concept captures how living entities, such as organisms, organs or cells, are transformed into technologically manipulated objects to know and enhance human life (Metzler and Webster 2011; Vermeulen *et al.* 2012). Bio-objects are not simply pre-given but are produced through practices, technologies, infrastructures, and knowledge cultures. They become the tangible product of such processes that 'can be leveraged and stored, as well as circulated and exchanged' and hold promissory value to render 'collective life safer, healthier, and more productive' (Metzler and Webster 2011). As such, bio-objects can be considered epistemic *and* material forms of becomings that take on novel shapes, meanings, uses, and values when brought into new spaces (Eriksson 2012). For example, social science literature has discussed the multiple identities the placenta can embody, such as waste (Waldby and Mitchell 2006), a commodity to be traded in bioeconomies (Kroløkke *et al.* 2018), or a research object, for example, transformed into placental cells (Lee 2016).

For our analysis, the placenta's identity as a research object is particularly relevant. Social science literature has traced the changing meanings of the placenta for biomedical research (Lappé and Hein 2022; Martin and Holloway 2014; Santoro 2011). Until the 1960s, biomedical and public perception of the placenta was dominated by the idea of the placenta functioning as a protective barrier for the foetus, despite some medical literature already stating otherwise (Martin and Holloway 2014). However, two medical tragedies surrounding the drugs thalidomide and diethylstilbestrol prescribed to pregnant women causing congenital disorders called this belief into question. These developments have reframed the placenta as porous to exposures, turning it into a valuable research object for studying how certain substances cross the placenta and impact foetal health (Colls and Fannin 2013).

These concerns about exposures during pregnancy led to various research directions, including a focus on studying the placenta to understand how early life experiences potentially have long-term health effects in adult life (Marsit 2016). In this regard, social scientists point to the seminal work of epidemiologists Barker and colleagues since the 1980s (Barker 2007; Barker *et al.* 2010), who studied the effects of undernutrition on foetal development and linked them to adverse metabolic outcomes in children (Lappé and Hein 2022; Yoshizawa 2016). These studies not only emphasise the placenta's porosity to its environment, but by connecting exposure experiences to future health, they have advanced a new temporal understanding of placenta research – one that ties the placenta to the well-being of the future body.

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Since then, new exposures such as endocrine-disrupting chemicals and molecular mechanisms have emerged as key research foci (Marsit 2016; Pasca and Penn 2010). However, the placenta remained on the sidelines of reproductive research until recently. Lappé and Hein (2022) argue that this shift in attention has been most pronounced in the last decade with the launch of the Human Placenta Project, a National Institute for Child Health and Development initiative that aims to fill knowledge gaps on the 'least understood human organ' despite its importance for reproductive health (Guttmacher *et al.* 2014).

Adding to this scholarship, we examine the specific promises of the placenta as a research object for *epigenetic research* rather than its value for the life sciences in general. We suggest that the placenta emerging in epigenetic research on air pollution exposure becomes a specific bio-object corresponding to the abovementioned postgenomic characteristics. Bringing STS literature on postgenomics into conversation with the bio-object concept, we develop the concept of the *postgenomic* bio-object to analytically engage with the discourse and practices we observed in epigenetic research. Focusing on the postgenomic dimensions of such objects moves our analytic gaze to examine not only how they can take on different identities when brought into new spaces (their potential multiplicity); instead, postgenomic bio-objects, as we will show, promise to capture the dynamic process of how biomaterials respond to their environments across time and how they exist in relation to these environments (and not as isolated entities). In other words, the specific characteristic of a postgenomic bio-object becomes its dynamic character during the research process. In the present case, this dynamic nature relates to (1) the placenta's characteristics as a developing and transitory organ and (2) the epigenetic mechanisms that are responsive to environmental exposures, particularly during the early life phase and across the life course. Such a take on bio-objects might contribute to theoretically and methodologically developing a biosocial perspective on birth cohort research.

However, drawing on Barad's (2007) theory of agential realism, every research setting and its apparatus of knowledge production requires 'agential cuts' to stabilise phenomena. These cuts produce contingent boundaries of phenomena, which enable 'the conditions for [. . .] description' (Barad 2007). In our case, the promise of capturing the dynamic character of postgenomic bio-objects across time invites us to scrutinise how researchers stabilise such phenomena in practice to perform research on them. We analyse where, when, and how researchers cut through the placenta and its relations (both materially and discursively) and how these cuts are commensurable with the idea of postgenomics in general and a postgenomic bio-object in particular.

Material and method

The study was part of the DFG-funded project, 'Situating Environmental Epigenetics. A Comparative, Actor-Centered Study of Environmental Epigenetics as an Emergent Research Approach in Three Research Fields', where we, among other aspects, investigated why and how scientists have adopted an epigenetic perspective in research on toxicants. Our research process was guided by the grounded theory methodology, which understands qualitative social science research as an inductive, recursive process that combines data collection and analysis to develop theory out of close empirical observations (Charmaz 2006; Strauss and Corbin 1998). Such an approach is particularly suited to explore quickly developing contexts, such as environmental epigenetic research. It involved repeated rounds of data gathering, open and focused coding, and memo writing to make sense of the research context we studied.

To understand how epigenetic knowledge on air pollution exposure is produced, the first author conducted an ethnographic study in a research programme on environment and child health at an institute for epidemiology and public health in Spain. The research programme investigates the effects of multiple environmental exposures on children's health and comprises

https://doi.org/10.1017/S0021932025000227 Published online by Cambridge University Press

approximately 60 scientists. For this article, we draw upon observations on a group of researchers involved in essentially all epigenetic-related research projects within the programme we call the EpiAir group hereafter (6 scientists in total).

Research in the programme is mainly centred around data gathered within their two prospective population-based birth cohorts located in the same province as the institute. The studies follow pregnant individuals recruited at their caregiving hospital and their offspring to assess exposure and outcome relationships. Cohort study A collected data from over 650 women and their children in a mid-sized city (ca. 200.000 inhabitants) since the mid-2000s; cohort study B collected data from 1100 participants in a major city (ca. 1.6 Mio. inhabitants) since the end of the 2010s. The sampling strategy was based on the following inclusion criteria: singleton pregnancy, ability to communicate in Spanish, no high-risk pregnancies, no assisted reproduction, and intentions to stay in the area where the cohort study is conducted during data collection. While cohort study A is part of a network of Spanish cohorts focused on investigating several environmental pollutants in air, water, and diet, cohort B has been explicitly developed and funded to understand the effects of air pollution on health and brain development.

The programme's epistemic interest in studying air pollution is tightly knit to the institute's location, an area struggling with air pollution levels. Simultaneously, while national and local contexts matter and shape how knowledge is produced, the institute's particularly international orientation and goal to improve global health create a research environment primarily interested in contributing to international networks and global research agendas on urban environments. As a result, national and local contexts were less explicit in their day-to-day epigenetic research activities.

The cohorts' database contains clinical, physiological, molecular, exposure and lifestyle data, including biological samples (blood, placenta, urine, saliva, hair, and nails). To collect exposure data on air pollution levels, particularly nitrogen dioxide (NO_2), particulate matter 2.5 (PM2.5), and black carbon, the cohorts have been using different methods, including predictive models for air pollution concentrations such as Land Use Regression, collecting data from passive samplers distributed at several sites across the study area linked to the residence address at birth, from individual exposure measurements at the households, and participants carrying passive samplers.

The EpiAir group mobilises data collected in these cohorts to investigate how children develop in relation to their urban environment. During Rossmann's fieldwork, the group was especially interested in the research question of how air pollution impacts neurodevelopment and whether environmental epigenetics is the mechanism to mediate such effects. The interest to focus on epigenetic mechanisms besides potential others lies in their characteristic to be highly responsive during critical windows of development. The group's findings will contribute to a larger consortium uniting several cohorts across Europe and North America. Their research is thus situated in a highly collaborative working environment typical for the present moment in environmental epidemiology.

Rossmann conducted fieldwork for one-and-a-half years between 2020 and 2022, both virtually and on-site. During this period, she participated regularly in the weekly scientific meetings of the research programme, project and consortium meetings, conferences organised by the programme, and workshops. On-site, she observed and participated in the day-to-day research activities of the lab, shadowing PhD students and a postdoc through their daily work routines, observing the preparation of biological samples at the hospital and the institute, accompanying fieldworkers to the homes of participants to collect data and the subsequent processing of data at their offices, observing the participants' gynaecological examinations, sitting with the researchers at their computers as they ran the statistical analysis with epigenomic datasets, and joining their lunches and coffee breaks. The ethnographic data we draw upon consists of fieldnotes, semi-structured interviews with research programme members (PhD students, postdocs, group leaders, 13 in total), documents collected (protocols, analysis plans, relevant scientific publications), and informal conversations with staff. We asked all interlocutors for informed consent and recorded

and transcribed the interviews. The researchers' names used in the following analysis are pseudonyms for anonymity reasons.

To analyse the empirical material, we followed a constructivist grounded theory approach using the content analysis software MAXQDA (Charmaz 2006). The enthusiasm for the placenta as a research object emerged early on as a salient theme. This prompted further investigations into the placenta's promises for epigenetic research on air pollution exposure. We began the analysis with an open coding phase to gain insight into how researchers construct the placenta's value to study air pollution exposure. Explorative questions such as what *is* and *does* the placenta in epigenetic research guided this phase. Second, we synthesised the most salient themes, among them 'defining and characterising the placenta', 'doing epigenetic research with the placenta', and 'negotiating the placenta's promises and challenges'. Third, we conceptually deepened our analysis by relating these themes to the bio-object concept (Vermeulen *et al.* 2012) and postgenomics as sensitising concepts. This step allowed us to explore further how scientists transform the placenta into a specific research object to understand biosocial dynamics and how scientists negotiate the methodological and empirical opportunities and challenges of working with birth cohort studies in postgenomics.

Empirical analysis: transforming the placenta into a postgenomic bio-object

Calling upon the placenta as a suitable research object

Why has the placenta become a suitable research object in the specific setting of epigenetic research for unravelling what happens between air pollution exposure and disease development? A closer look at the researchers' narrations of why they have turned to the placenta illustrates the epistemic potentials ascribed to this organ. In this section, we unpack the different rationales proposed by the EpiAir group to show how they discursively call upon the placenta as a research object that embodies what we propose to be a postgenomic epistemology.

The placenta as accessible

The first rationale is tied to the specific research context of conducting human population-based research that has enabled the placenta to become a suitable research object to study air pollution exposure in epigenetic research. Mafalda, the EpiAir group leader, illustrates this point when asked why the placenta is so intriguing to analyse:

> We are working with human beings, so it's very difficult with biological samples. [. . .] we are restricted to two types of samples [for epigenetic analysis], that is blood and placenta, and given that the placenta is the organ that determines all foetal development, we think it's really important for this. (Interview Mafalda 1)

The restriction to only some biological samples that Mafalda mentions links to a more general criticism faced by environmental health scientists conducting epigenetic research with cohorts: using proxy markers, predominately blood, to study epigenetic changes and their limited validity. Scientists use proxy markers to infer something about other places in the body that are not accessible, for example, for ethical reasons or the impossibility of taking biopsies without threatening the participant's livelihood. However, epigenetic changes are tissue-specific: every tissue is characterised by different cellular compositions, and every cell in the body has its own epigenome. Thus, it matters where researchers take samples to make statements about epigenetic changes at specific places in the body.

The group has only recently started to analyse placenta samples besides blood samples. Having mainly the option to choose between blood and placenta, they link the question of accessibility to the placenta's role in regulating foetal development, as Serena, a postdoc, highlights:

https://doi.org/10.1017/S0021932025000227 Published online by Cambridge University Press

> Most of the studies before focused on cord blood, but cord blood probably doesn't tell you so much about what's really happening in the foetus. The placenta has a main role in the development of the foetus and its malfunction may actually be more related to what's happening in the foetus. (Interview Serena)

Both quotes illustrate how our interlocutors frame the placenta as the epistemically more adequate biomaterial to study foetal development, in which tissue-specific epigenetic changes can be accessed.

Unlike other tissues, researchers can relatively easily collect placenta samples from the cohort participants due to dominant Western cultural ascriptions of the placenta turning into waste after birth (cf. Waldby and Mitchell 2006). Thus, the placenta as waste is revitalised through the scientists' imaginations for its central role in regulating foetal development via epigenetic changes. Our analysis shows how choosing a certain biomaterial is tied to its ascribed epistemic value *and* results from practical considerations and cultural norms concerning the accessibility of tissues. Simultaneously, accessing health information via the placenta incorporates cultural and social norms to know the environment and its effects through the maternal body.

The placenta as relational

The second rationale our analysis reveals is that the placenta gains epistemic value because of its positionality between the pregnant woman and the foetus. As Pola, one of the network's principal investigators, argues: 'The placenta is fantastic. [. . .] It's the bridge between two organisms. This is incredibly amazing I mean it's like wow . . . it's the link between the mother and the child.' (Interview Pola) It is not hard to miss Pola's fascination when asked about the placenta. Highlighting its relationality positioned between mother and child, the EpiAir group inscribes itself into a tradition of biomedical research that investigates their interactions.

Placenta research has been challenging medical and cultural concepts of bodily integrity and autonomy by overcoming ideas of the placenta as an absolute barrier between the mother and the foetus (Martin and Holloway 2014). Biomedical literature understands the placenta as a temporary organ that forms from foetal DNA in the first three months of pregnancy and takes on essential physiological functions to sustain foetal life (Burton and Fowden 2015). It describes its main function as transferring nutrients, waste, gas, oxygen, and toxicants in and out between the maternal and foetal blood circulations. The placenta is further discussed as crucial to maternal and foetal physiology during pregnancy as it produces and regulates hormones affecting both the mother and the foetus. Thus, contemporary biomedical literature emphasises the intimate ways the mother, the foetus, and the placenta interact as a dynamic system (Gundling and Wildman 2015).

According to our interlocutors, the placenta, as this unique relational space, has become particularly interesting to localise air pollutants entering the maternal bloodstream and their effects on the developing foetus. In the programme's weekly scientific meeting, Lucy, a PhD student, explains that research has shown that air pollutants cross the placental barrier, going '*inside* the placenta'. Emphasising the air pollutants' ability to translocate into the placenta is an often-used rationale by the group for studying this particular organ. As Serena argues:

> It's very interesting trying to understand [. . .] if the air pollutant in that specific location is really affecting placental function and how it can affect the foetus. [. . .] There are different lines of research and one is: is air pollution affecting the epigenetics locally in the placenta and can we identify markers that can relate to foetal development? (Interview Serena)

This quote illustrates how the research group understands air pollutants, the maternal body, the placenta, and the foetus as relational. In doing so, studying the placenta becomes a resource to

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make sense of how environments and the foetus interact to better understand the health effects of air pollution exposure.

The placenta as responsive

As a third rationale, the EpiAir group proposes the placenta as a responsive organ to its environment that has agency in dealing with exposures. At the research programme's weekly scientific meeting, Layla, a postdoc working in the EpiAir group, introduces the placenta as a 'mediator' of environmental exposures. She highlights the placenta's role in protecting the foetus from the harmful effects of toxic exposures through 'adaptive responses', for example, via epigenetic regulation. To make these mediations visible, Layla plans to analyse the 'placental molecular landscape' as a proxy of placental function. She explains to her colleagues that several studies have shown how exposure-induced epigenetic changes alter the expression levels of placental genes involved in, for example, development, energy metabolism, and immune response and are functionally linked to adverse and often delayed reproductive and neurodevelopmental outcomes in the offspring.

Layla proposes an understanding of the placenta that *translates, deals with, and buffers against* exposures to adapt its care for the foetus. This idea of the placenta as a mediator that has agency is also discussed in the biomedical literature the group considers relevant for their work:

> There is now clear evidence that the placenta is not just a passive conduit from mother to fetus, but that it is able to respond to supply signals arising from the mother and demand signals emanating from the fetus. (Burton and Fowden 2015)

> The placenta also acts as a selective barrier, detoxifying xenobiotics and inactivating maternal stress hormones in order to provide a stable milieu in which the fetus can develop. (Burton *et al.* 2015)

Both articles emphasise the placenta's role as more than a conduit or filter but as an active agent for creating the milieu in which the foetus develops. According to the group's hypothesis, when an air pollutant arrives in the placenta through the mother's bloodstream, the placenta translates the toxic exposure into an epigenetic change at a specific locus in a placental cell, which, in further consequence, proliferates through placental tissue by an army of activated enzymes, ultimately affecting the foetus' regulatory system. Through this process, air pollution and the placenta change in the mediated situation: It is not only the external environment that potentially harms the placenta, but also the placenta does something to the air pollutant by detoxifying it through metabolic processes or translating it into an epigenetic signal. As such, it can either protect the foetus through an adaptive (epigenetic) response or, under certain circumstances, negatively affect the offspring's health trajectory (e.g. restricted growth) (cf. Burton *et al.* 2015). Thus, it is the mediating capacity of a particular placenta that creates the pollutants harmfulness for the foetus. This characterisation emphasises the variability between placentas and their agential capacities in dealing with exposures.

These rationales of characterising the placenta as relational, responsive, and agential illustrate how the organ can be considered a (hypothetical) postgenomic bio-object to capture the temporally dynamic interactions between the foetus and its surrounding environments. Simultaneously, the placenta is a biomaterial easily accessible within birth cohorts as an essential resource for epigenetic research. This merging of epistemic and practical considerations turns the placenta into a suitable research object for studying air pollution exposure in epigenetic research. Concerning biosocial theory, the ideas of relationality and responsiveness open up ways to think about thicker understandings of environmental exposures and bodily processes as situated phenomena that emerge in everyday practices.

https://doi.org/10.1017/S0021932025000227 Published online by Cambridge University Press

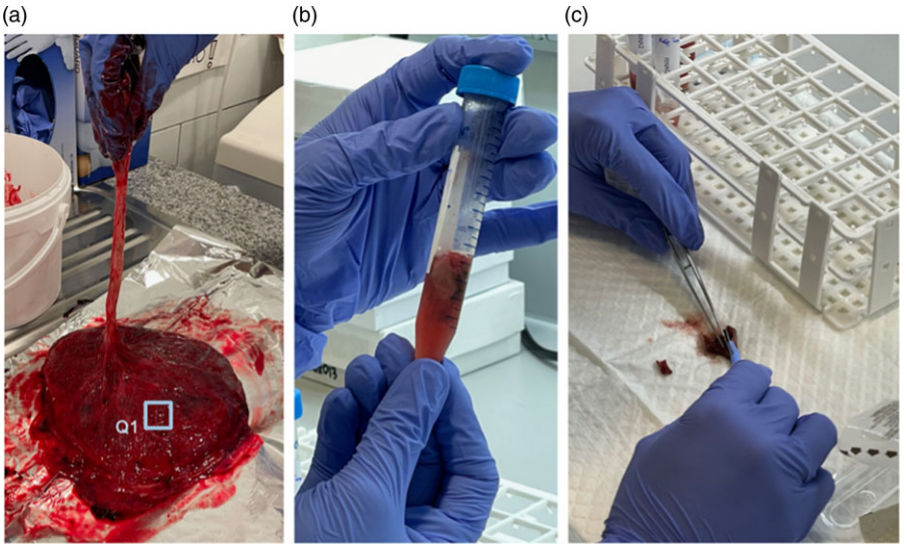

Figure 1. Processing the Placenta at the Hospital (Credits: Rossmann).

Producing a postgenomic bio-object: between epistemic potentials and practical research realities

How does the promise of the placenta as a postgenomic bio-object relate to the practices of doing epigenetic research with birth cohorts? Our interlocutors frequently problematise the epistemic limitations of only having access to the postpartum placenta, as becomes evident when discussing the developmental importance of the different trimesters. Due to the placenta's characteristic to continue to form and develop during pregnancy, a placenta in the first trimester is different from the one later on, as Layla emphasises: 'It would be great to study the [placenta] at different trimesters but not possible.' (Interview Layla) On the one hand, the group values the placenta's 'not-yetness' that characterises bio-objects and their peculiar temporalities (Eriksson and Webster 2008), such as potentially evolving differently depending on the experiences it makes during pregnancy. On the other hand, this characteristic is also its limitation as an organ that only becomes accessible after birth.

To elucidate this tension, we first examine the concrete practices of how the postpartum placenta is made into a bio-object for epigenetic analysis. We show how the EpiAir group decontextualises the placenta from its former environment to analyse exposure-induced epigenetic changes as the key information. We draw on the term decontextualisation to discuss the material practices of preparing the whole placenta for epigenetic analysis and their epistemic consequences. We then discuss the implications of these practices to redeem the placenta's promise as a postgenomic bio-object.

Turning the placenta into a postgenomic bio-object

To make the epigenetic information on exposure-induced changes accessible, the group moves along a chain of reductions: *whole placenta* → *biopsy* → *smaller fragments* → *liquid* → *data*. This chain starts at the collaborating hospital. As quickly as possible after a cohort participant gives birth, gynaecologists cut out four *biopsies* of the placenta (Fig. 1A).

According to the protocol, the gynaecologists need to prepare the samples in a particular way and at a specific time (after delivery) to ensure their comparability within the cohorts, as Serena highlights:

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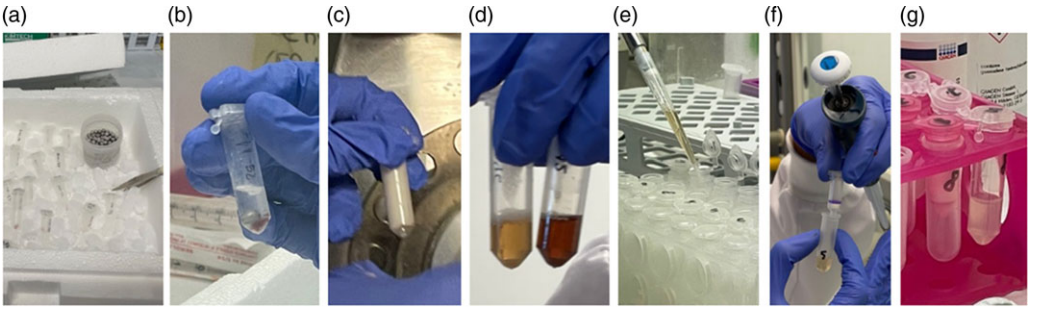

Figure 2. Turning Placenta Bits into DNA and RNA Probes (Credits: Rossmann).

> The blood flow is different in the different sections and the mechanisms are not homogeneously distributed across the placenta. So it's important [where exactly the biopsies are taken from], it's also about the concentration and the amount of epigenetic changes that you can find in one site or the other of the placenta. (Interview Serena)

This quote illustrates how the placenta cannot be assessed as a whole organ due to its biological and cellular heterogeneity. Instead, researchers organise the placentas into two sides: the maternal side facing the uterus and the foetal side on which the umbilical cord is attached. To ensure the production of comparable research objects, the group decided on a specific section five cm away from the umbilical cord, avoiding too many blood vessels becoming part of the biopsies to produce homogeneous samples.

As a second step, the biopsies travel several floors upstairs, where a lab technician further prepares them by cutting them into four *smaller fragments*: the foetal membrane, the maternal decidua, the upper and lower foetal villi (Fig. 1C). It will be the upper foetal villi that the group analyses for epigenetic changes understanding it as the 'zone of exchange' as Layla explains. The tree-like structure of the villi is made of foetal blood vessels, which are covered by foetal cells and anchor into the uterine wall during placentation (Colls and Fannin 2013). As Colls and Fannin (2013) detail, contemporary biomedical literature characterises this part as the space where 'oxygen, nutrients, and hormones are passed into the foetal blood vessels, and waste products from the foetus are removed to be disposed of by the mother's body'. Considering the foetal villi as the 'zone of exchange' where the effects of toxic exposures on foetal development can be localised, the group enacts this part as the epistemically most relevant placental fragment.

Third, at the institute's laboratory, Layla and Stephanie, a PhD student working closely with Layla, further transform the foetal villi fragment into *liquid* for DNA and RNA extraction (Fig. 2). On their workbench sits a polystyrene box filled with ice with 24 tubes containing flesh-coloured pieces sticking out (Fig. 2A). What looks like bacon bits turns out to be 30mg of the upper foetal villi. To prepare them for DNA and RNA extractions, Layla and Stephanie homogenise the tissue first using lysis, a toxicant to break down cell membranes, and little stainless-steel beads (Fig. 2B). A carefully developed procedure follows for further breaking down the fragments via multiple steps, using buffers and beads until they are turned into liquid, neatly divided into two tubes containing the invisible extracted DNA and RNA (Fig. 2C-G).

As a fourth step, the DNA sequencer turns the liquid from the tubes into *data* on epigenetic changes. These datasets, one on DNA methylations and one on RNA modifications, contain information to understand where exactly in the genome genes or gene regions are differently expressed due to air pollution exposure compared to reference placental expression profiles established by previous studies.

Lastly, the researchers put the epigenetic data from the sequencing facility to work. Stephanie sits at a personal computer preparing the epigenomic analysis run on exposure-induced DNA

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methylation changes. She uploads the relevant datasets into the statistic programme R: first, the methylation data extracted from the postpartum placenta; second, all relevant meta-data about the cohort participants (e.g. sex, age, ancestry); and third, the exposure data they collected within the cohort studies. In the case of air pollution, this means data on the different levels of air pollutants: nitrogen dioxide (NO_2), particulate matter 2.5 (PM2.5), and black carbon. The dataset also contains potential covariates such as maternal education or season of conception that could affect DNA methylation on its own or with the exposure of interest.

Stephanie initiates the epigenomic analysis run. After a while, a table appears on the screen listing the first top DNA regions, so-called CpG sites, where a guanine nucleotide follows a cytosine nucleotide. Stephanie looks at the p-value of each CpG site to check if this particular site is significantly associated with exposure to one of the air pollutants. Next, she examines the beta value and explains that '0 means the site is not methylated, and one means the site is fully methylated'. When a site is fully methylated, it can no longer be expressed by the transcription machinery and thus potentially 'silencing' this gene region. Based on both values, Stephanie will create a list of the most interesting CpG sites and start with their biological interpretation, assessing if these sites are close to a gene that previous studies have associated with neurodevelopmental outcomes.

The chain of reductions that began with the whole placenta ends with the final results of the statistical analysis gaining information on the epigenetic pattern at a specific locus in the genome: change in methylation yes/no. This result simplifies the complex interaction between air pollution exposure and biological response to a static logic of one air pollutant causing a material change at one point in time within a binary system of 0–1.

Defying the promise of the postgenomic bio-object

Following the steps of how different actors transform the placenta into a bio-object to know and enhance human life, we see how the EpiAir group moves along a chain of reductions. To extract what they consider the essential epigenetic information, they decontextualise the placenta from its former environment on the material and epistemic level to become, as Layla phrases it, 'as clean as possible'. Through this cutting, picking apart, processing, and purifying, they transform the biological and cellular heterogeneous organ into new entities until it is reduced to a dataset on epigenetic changes.

However, analysing these practices shows how the research realities in birth cohorts defy the promise of the placenta as a postgenomic bio-object. Regarding the second rationale of relationality, the dominant methods and technologies to extract and process epigenetic information make it necessary to decontextualise the placenta from its environment. In doing so, they take the body and air pollution exposure out of its surroundings and turn the placenta into a static, isolated bio-object that loses some of its relational character. While this type of analysis provides correlative evidence between one exposure and epigenetic changes in tissue profiles, it misses out on showing how these relations develop over time. Regarding the third rationale of responsiveness, since the placenta is only accessible after birth, i.e. at one point in time, researchers gain limited insights into how it dynamically responds to its environment during pregnancy. Instead, the analysed samples only make visible the accumulation of all experiences up to this point.

Current research methods and infrastructures challenge how our interlocutors can translate biosocial dynamics, particularly the temporal scales of exposure and effect, into feasible research designs that are often pragmatic (e.g. based on the availabilities of data, biomaterials, and technologies). Such practices raise the question of what gets decontextualised (and what does not), for which reasons, and the implications of these choices. As scholarship in the social sciences points out, being reductionist is a central epistemic practice to reduce complexity in knowledge production (Beck and Niewöhner 2006). Reality constantly threatens to overflow the neatly

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constructed boundaries of research designs (Nelson 2018). As discussed in the previous section, our interlocutors sometimes acknowledge the practical reductions they engage in, for example, as posed by the limited accessibility of tissues at different times within cohorts. In other moments, Layla reflected upon accepting trade-offs between more standardised biopsies and making it still feasible for their collaborators to be willing to collect samples despite their primary task of delivering babies:

> I had to adapt the protocol a bit because in a hospital, [. . .] sometimes things get distracted because, of course, the health of the mother is more important than the sample. Sometimes we realise it took longer to freeze the sample than other times. Here in the lab, I could clearly see it because the RNA [in the sample] was more degraded [than usual]. [. . .] You cannot control these things. It's what happens with the placenta and with humans. (Interview Layla)

Here, time becomes an unwelcome environmental factor that is difficult to control. Such accounts make tangible the practical challenges of conducting research with birth cohorts, leading the EpiAir group to operate within the boundaries of their research context.

However, these practical reflections overlook epistemic constraints built into the design and method of cohort studies and epigenetic research. First, the practices to analyse the placenta illustrate how these methods construct air pollution as a stable, quantitative entity. Linking exposure variables to adverse epigenetic changes promises to provide robust statistical evidence of the link between air pollution and health effects. In societies where 'numbers drive policy', such evidence is necessary and has 'authoritative power' to show that these effects exist (Roberts 2021). However, these numbers simplify reality by isolating air pollutants from the spatial and social context that also constitute air pollution and its effects on situated bodies. Second, the research design might unintendedly reinforce a focus on the relationship between the placenta and the foetus in epigenetic research with less attention on the pregnant person and their exposure experiences. One could get the impression that their main role is to provide the reproductive material to study foetal development. This tendency reproduces a more general imbalance in postgenomic research that marginalises the health effects on women while simultaneously paying disproportional attention to the maternal body for foetal health, as has been critically discussed by feminist scholars (Lappé 2016; Richardson 2015).

Reviving the postpartum placenta as a postgenomic bio-object

How does the EpiAir group deal with this tension between the epistemic potentials of the placenta and the practical realities of doing epigenetic research with birth cohorts? In this section, we analyse three strategies for how researchers deal with these limitations by collecting additional data at other times in and around this organ to recontextualise the epigenetic analysis performed on the postpartum placenta. We show how they complicate their research apparatus of isolating the unidirectional effect of one exposure variable and its biological effect.

Finding (more) environment in the placenta

The first strategy of how the EpiAir group recontextualises the postpartum placenta is by generating data on air pollution levels using the additional placental biopsies the gynaecologists prepared. Collaborating with another research group, they examine the number of black carbon particles in the biopsies by conducting a histological analysis with a laser scanning microscope. Through the microscope's images, the material components of black carbon exposure become visible as little white dots against the tissue structure's fluorescent green and black background.

Interpreting these images allows the group to hypothesise how the placenta deals with and protects the foetus from air pollution exposure. They currently discuss the possibility that the

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amount of air pollutants found in the histological analysis might not correlate to the cohorts' exposure data used in the epigenomic analysis, as Mafalda argues:

> [The study] proves that the particles are there in the placenta. But I don't know if the *quantity* will be *proportional* to the exposure. [This could] be due to biological issues. If the placenta or the liver or whatever can detoxify the particles better than another person. Maybe your placenta has less particles but this does not mean that you are exposed to lower [air pollution] levels. (Interview Mafalda 2)

Mafalda suspects that the number of particles inside the placenta might differ from the one encountered outside due to its ability to detoxify them. By quantifying and contrasting these levels, a narrative of the placenta emerges as more than a repository for environmental exposures but actively responding to and managing them.

Analysing the microscope's images promises to show the placenta's postgenomic dimension as the responsive organ they ascribe agency to in dealing with exposures. It is again the milieu of the placenta that creates the toxicant's harmfulness for the foetus and individualises how the placenta has dealt with the exposure. Thereby, the number of black carbon particles found in the biopsies produces forms of difference between placentas, which resonates with individualised perspectives on health that have become central to postgenomics. However, this data stems from the same biopsies taken at the same time as the ones used for the epigenetic analysis. This again limits what the group can know about the temporally dynamic process of disease development during pregnancy.

Tracking the pregnancy placenta

A second strategy of how the EpiAir group recontextualises the pregnancy placenta is by collecting additional blood samples to infer how the organ responds to air pollution exposure during pregnancy. Recently, the group has become especially interested in extracting extracellular vesicles (EV) from maternal blood samples originating from the placenta and circulating through the maternal bloodstream. These vesicles are essential in cell-to-cell communication as they can traffic molecules through the body, such as microRNAs, that regulate gene expression in recipient cells. Recent studies have found that environmental exposures such as air pollution can influence the content and release of EVs into the bloodstream and regulate the mother's immune function, which could impact the development of the placenta. Thus, EVs are hypothesised to be 'a powerful mediator of environmental stimuli' and a 'promising mechanism to help explain how these environmental exposures are able to "talk" with the molecular machinery of the body' (Neven *et al.* 2017).

The group's excitement for studying microRNAs in placenta-derived EVs becomes evident during Layla's presentation at the programme's weekly meeting. She explains that these vesicles secreted from the placenta are thought to be 'one of the main mechanisms of communication between the mother and the foetus'. Analysing EV-derived microRNAs promises to generate additional epigenetic biomarkers and recontextualise the epigenetic information extracted from the postpartum placenta. Additionally, as Mafalda explains, extracting EVs allows the group to 'reach the organ that you cannot reach otherwise' and emerge as 'a strategy to solve the problem of the tissue that we have in epidemiological studies' without physically touching the placenta (Interview Mafalda 1).

These promises of analysing EVs connect two of the postgenomic dimensions the group calls upon. First, EVs tell a relational story of how the placenta, the foetus, the mother, and the environment interact via an elaborate and dynamic system of cell-to-cell communication. Second, analysing microRNAs in EVs produces information on the placenta's responsiveness across time. Once collected, data on aberrant microRNA patterns in EVs allows them to track the development

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of the placenta at multiple time points during pregnancy. The group plans to compare their findings on gene expression changes in the postpartum placenta to those in EV-derived microRNAs. In doing so, this data is turned productive for clinical interpretations, as Mafalda argues:

> We want to see the association between air pollution, the microRNAs inside these vesicles and the neurobehavioural outcomes. And the interesting thing about these extracellular vesicles is that you can measure them at the beginning of pregnancy. So you can anticipate what is going to happen. [. . .] You can try to create a biomarker for [predicting which] children will have neurobehavioural complications in the future due to prenatal air pollution [exposure]. (Interview Mafalda 2)

Understanding EVs as a resource for predicting and anticipating health outcomes creates another temporal layer in the spacetime of pregnancy. Connecting findings on aberrant epigenetic changes in the present to future health effects they frame as an opportunity for early interventions on the 'not-yet-sick' child and an avenue for enhancing human life as the bio-object's promise.

Linking the brain to the placenta

As a third strategy, the EpiAir group uses imaging technologies to obtain data on brain development and link this data to the effects of air pollution. Cohort study B currently collects two types of images during pregnancy and after birth, which they use as estimates of neurodevelopment. For the first type, gynaecologists conduct an abdominal ultrasound during the pregnancy week 32. These images allow the researchers to assess the structural integrity and level of maturity of the foetal brain and to detect abnormalities of the central nervous system. This includes measuring the size of the brain to check if it develops according to charts.

Additionally, the group plans to conduct fMRI scans of the brain for a subset of the cohort when the newborns are roughly one month old to track brain development over time. fMRI technology measures brain activity by tracing blood flow changes connected to neuronal activation. Layla reiterates their epistemic importance by framing these scans as 'super valuable' because they provide markers of cortical and white matter myelination that give evidence of brain development, neurodegeneration, and plasticity.

Producing this kind of data comes with the promise to look inside the foetal and child brain and better understand the complex process of neurodevelopment. Layla argues that 'having these tools, the fMRI or the neurosonography, you [get] closer to the brain, [. . .] closer to what's going on there' (Interview Layla) – as compared to more traditional tools such as psychological tests or questionnaires to asses neurodevelopment. However, these practices reduce neurodevelopment to a physiological understanding coupled with indicators such as size and structure. Once collected and analysed, the EpiAir group plans to compare these images to their findings in the postpartum placenta to see if the phenotype matches the prediction made with the epigenetic data.

Linking anatomical and functional measures of the brain to alterations in the placental epigenome revives the postpartum placenta as the relational organ situated between the environment, the mother, the foetus, and its brain. This extends the spacetime of pregnancy into the future of a child's brain development and the past 'to what occurred in utero' (Lappé and Hein 2022). The group hopes to confirm previous studies showing, for example, that changes in the placental epigenome led to alterations in gene expression on the hypothalamic-pituitary-adrenal axis, compromising how the brain develops.

These practices of assembling demonstrate a specific mode of creating evidence indicative of how postgenomic sciences produce knowledge about how phenomena interrelate (environments, bodies, organs, epigenomes, and temporalities). They can be considered modest attempts to complicate methodological approaches and integrate biosocial views on health and illness that

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social scientists have called for (Chiapperino 2024; Chiapperino and Paneni 2022; Lamoreaux 2023). While tracing epigenetic changes in the placenta remains the central biological mechanism of interest, by generating these additional data derived from biopsies, blood samples, and brain images, researchers revive the temporal importance of the placenta as a developmental organ and rescue it from its limitations of being collected postpartum. The first two strategies give insights into what happens in the placenta during foetal development. The third strategy extends the gaze into the future and the effects of air pollution exposure on children's neurodevelopment. Putting this data to work allows the researchers to recontextualise the epigenetic data extracted from the placenta and to substantiate their claims on the temporally dynamic process of disease development and future child health.

Conclusion

This article aimed to investigate the transformation of the placenta into a postgenomic bio-object. We demonstrated how researchers deal with the epistemic tension between the placenta's discursive promises for elucidating biosocial dynamics and the practical research realities in postgenomic sciences. Pairing STS literature on postgenomics with the concept of bio-objects (Vermeulen *et al.* 2012) offers a generative perspective to study how postgenomic researchers produce the placenta as a specific bio-object marked by dynamically becoming with the toxic and maternal environment it is embedded in. By developing the idea of postgenomic bio-objects, this article contributes to analytical and empirical discussions on how researchers attempt to study biosocial dynamics in the face of the material, technological, and infrastructural possibilities and limitations of working with birth cohorts. In practice, the postgenomic bio-object is not the placenta alone but the assemblage of data gathered in and around this organ. That is, a postgenomic bio-object not only emerges from one entity (e.g. tissue or cells) transformed into a research object but becomes meaningful as an assemblage of knowing about a phenomenon. In our case, this assemblage consists of additional data derived from biopsies, blood samples, and brain images that are curated – that is, actively chosen among potential others –to know the temporal process of disease development. Showing the temporal and relational aspects is a key feature of these assemblages to make claims about the effects of air pollution exposure on foetal development and future child health.

Building on these ethnographic findings, we see two potential entry points for cross-disciplinary reflexive engagement. To be sure, we do not attempt to solve the problems we encountered in our study by proposing a universalist, all-encompassing biosocial framework. Instead, we aim to advance modest interventions to strive for thicker accounts that recontextualise exposure and biological mechanisms in the life worlds and practices of the participants.

First, by tracing the material practices of decontextualisation, we demonstrated how researchers and their experimental apparatus fix air pollution, bodies, placentas, and toxicity at specific moments to stabilise biosocial dynamics. These agential cuts produce a particular version of the placenta as a postgenomic bio-object and influence which bodily processes at what points in time come to matter in biosocial research. While agential cuts are always necessary to enact phenomena, cutting '"things" together and apart' has ethical and socio-political consequences for understanding phenomena such as health and illness (Barad 2007). Ethnographic research makes explicit the choices made to produce evidence on adverse health effects and what potentially gets lost to understand biologies as situated in time and place (e.g. exposure as lived experiences, complex time-scales of disease aetiologies).

Here, STS can provide critical tools to reflect upon taken-for-granted assumptions about biology. 'Studying up' to the scientists with institutional, cultural, and financial power rather than 'studying down' to the cohort participants allowed us to make explicit the epistemic tensions the placenta produces with the current tools and methods available. These insights offer a starting

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point for developing innovative approaches that encourage *reflexive engagement* with biosocial research practices in cohort studies. STS has a long tradition of reflecting upon what its methods do in the social worlds they study (Law 2004). Conducting ethnographic research creates interference with the studied contexts and opens up spaces for life scientists to reflect upon their practices (Müller and Kenney 2014; Rossmann and Samaras 2024). As Müller and Kenney (2014) point out, such interferences may appear 'small, mundane and often unintended', but they disrupt routinised ways of thinking about epistemic practices. In our case, one entry point could be to discuss the moments when our interlocutors openly grapple with the limitations of placenta research, such as accessing it at different points in time, and the strategies they develop for making claims on adverse health trajectories nonetheless. In these modest moments, we recognise fertile ground to collaboratively work out these epistemic tensions through ethnographic research. Making them available for reflexive discussions on one's epistemologies during the research process (and not after) helps to better understand how the social 'gets under the skin'.

Second, the concept of a postgenomic bio-object lends itself to reconsidering what type of data research needs to recontextualise biosocial processes. Such considerations offer new opportunities for innovative mixed methods approaches. They could build on cross-disciplinary approaches such as bioethnography, which uses qualitative ethnographic data about participants' life worlds that feed back into developing better research questions and numbers for understanding health trajectories (Roberts 2021). One potential avenue could be to generate qualitative data on how the spatial and socio-political conditions of specific neighbourhoods the cohort participants live in (e.g. built environment or traffic policies) play into experiences of air pollution exposure. Ethnographic research helps clarify how air pollution and its bodily effects emerge differently in participants' everyday practices. Life scientists could benefit from these engagements by reflecting upon their research choices that often remain implicit and making them part of a deliberate decision-making process when designing studies. Social scientists, in turn, must ask themselves how much context can be reintroduced and where we must learn to put aside some complexities to make research feasible and produce new results on health outcomes and their causes (Roberts 2021). While this is a complex and time-consuming task that necessitates funding schemes supporting such collaborations, we see great opportunity in such projects to better understand the biosocial complexities of human health and illness.

Acknowledgements. We would like to thank the anonymous reviewers and the editors of the special issue–Sahra Gibbon, Rebecca Hardy, Dominique Behague and Emily Emmott–for their thoughtful comments and valuable feedback, as well as the editors of the Journal of Biosocial Sciences for their assistance. We would also like to thank our project colleagues Georgia Samaras and Michael Penkler, the Science & Technology Policy Research Group at TUM, Patrick Bieler, Amy Clare, Morgan Meyer, and Jörg Niewöhner for their invaluable and thought-provoking commentaries on earlier versions of this article and Nicole Nelson for suggesting the concept of the bio-object as a suitable lens for our analysis. Finally, we are grateful to the researchers who took the time to participate in our study.

Funding statement. This work was supported by the German Research Foundation under Grant 403161875.

Competing interests. The authors declare none.

Ethical standard. The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008. The free and informed consent of the subjects or their legal guardians was obtained.

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Cite this article: Rossmann S and Müller R (2025). Unravelling biosocial dynamics? The placenta as a postgenomic bio-object in environmental epigenetic research on air pollution. *Journal of Biosocial Science* 1–19. https://doi.org/10.1017/S0021932025000227