Environmental Research 280 (2025) 121926

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Maternal exposure to Waste-to-Energy plants and risks of adverse birth outcomes and hypertensive pregnancy disorders in Lazio, Italy

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ARTICLE INFO

Keywords:
Waste
Incineration
Birth defects
Pre-eclampsia
Gestational
Air pollution
Difference-in-differences

ABSTRACT

Evidence on the effects of waste incineration on adverse birth outcomes (ABO) and hypertensive disorders of pregnancy (HDP) is limited. We investigated the association between maternal exposure to a waste-to-energy (WTE) plant in Lazio Region and ABO/HDP. Employing a difference-in-differences (DiD) design, we assessed changes related to the plant's deactivation (2017), comparing outcomes to a control WTE plant that remained operational.

Mothers with geocoded residential address within 7 km from Colleferro (exposed area) and San Vittore del Lazio (control area) plants who delivered between 2007 and 2023 were enrolled. Information was derived from regional health databases.

Outcome-specific multivariate logistic models included interaction terms between a "pre-post" variable (0 for deliveries in the operational period - 1 for deliveries in the post-operational period) and a variable indicating the plant (Colleferro/San Vittore) linked to each delivery. Secondary analyses considered extended buffers around the plants or a control group from a broader area surrounding Colleferro, instead of San Vittore.

25,360 deliveries occurred within 7 km from the two WTE plants. After Colleferro plant's deactivation, pre-eclampsia risk decreased compared to San Vittore (OR = 0.35; 95 % CI: 0.13–0.93). Suggestions of association were noted for ABO, for example preterm birth (OR = 0.83; 95 % CI: 0.62–1.10). Pre-eclampsia risk remained low when using an extended buffer for the delivery selection.

Exposure to WTE plant emissions was associated with ABO and HDP. While further research is needed, public health measures should enhance stricter emission monitoring, cleaner waste management, and prevention for pregnant women in affected areas.

1. Introduction

Thermal treatment of waste, including processes such as combustion, pyrolysis, and gasification, is extensively utilized for handling municipal solid waste, industrial waste, and solid refuse fuels (Lombardi et al., 2015). This approach significantly reduces both the mass and volume of waste, thereby decreasing the reliance on landfill disposal and mitigating sanitary issues associated with waste decomposition (Gohlke and Martin, 2007). Modern thermal treatment facilities, commonly known as waste-to-energy (WTE) plants, are designed to burn municipal solid waste to generate electricity and/or heat. WTE plants aim at reducing waste volume while recovering energy, positioning themselves as part of sustainable waste management strategies. Despite their benefits, local communities often resist WTE projects due to concerns over health risks, odors, and visual impacts. There are concerns about local air quality because, despite emission control technologies, WTE plants release pollutants like particulate matter (PM), nitrogen oxides, sulfur dioxide, and trace amounts of dioxins and heavy metals (Waste Incineration and Public Health, 2000).

Previous systematic reviews (Giusti, 2009; Porta et al., 2009; Mattiello et al., 2013; Ashworth et al., 2014; Vinti et al., 2021) have already highlighted several health concerns related to living near incinerators and WTE facilities, including associations with adverse reproductive outcomes, that is also the main issue of this study. These findings suggest an association with infant mortality, congenital anomalies, neonatal mortality, preterm delivery, and low birth weight. However, studies included in those reviews may suffer from biases due to design flaws, lack of accurate exposure data, and inadequate control of confounding

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https://doi.org/10.1016/j.envres.2025.121926
Received 3 March 2025; Received in revised form 20 May 2025; Accepted 22 May 2025
Available online 22 May 2025

factors. Evidence about the health effects of new-generation incineration plants is still limited, with a recent systematic review pointing out little to no evidence of potential adverse health outcomes of living near a latest-generation incinerator, based on the few number of studies conducted to date (Negri et al., 2020).

Birth defects comprise a broad spectrum of congenital anomalies. Their global prevalence at birth was estimated to be around 2–3 % (Corsello and Giuffrè, 2012). Among all anomalies, congenital heart defects are the most common subgroup of malformations, with an estimated prevalence ranging from 1 case in 100 births (1 %) (Schwedler et al., 2011; Santana, 2018; Nousi, 2010) to 5 to 8 cases in 1000 births (0.8 %) (Massaro and Donofrio, 2010). Preterm birth and low birth weight are adverse outcomes of concern as well because they can lead to severe short- and long-term consequences on various organs (Hubbard et al., 2023; Chehade et al., 2018; Humberg et al., 2020; Inder et al., 2023; Reyes and Mañalich, 2005; Andrade et al., 2024).

Also air pollution, produced as well by WTE plants, is increasingly being considered a risk factor for birth defects, with recent systematic reviews pointing out associations between maternal exposure to outdoor pollutants and the occurrence of anomalies in the newborns (Melody et al., 2019; Bekkar et al., 2020; Luo et al., 2021; Boogaard et al., 2022).

Previous studies have analyzed associations between prenatal exposure to incinerators emissions and WTE plants and congenital anomalies (Vinceti et al., 2008, 2009, 2018; Cordier et al., 2004, 2010; Parkes et al., 2020; Cresswell et al., 2003), low birth weight (Candela et al., 2013; Santoro et al., 2016; Ghosh et al., 2019; Lin et al., 2006; Tango et al., 2004), and preterm birth (Candela et al., 2013; Ghosh et al., 2019; Lin et al., 2006; Piccinelli et al., 2022; Santoro et al., 2016). Some of these studies have utilized dispersion models to estimate exposure levels, while others relied on proximity as surrogates of exposure.

Hypertensive disorders of pregnancy (HDP) include conditions such as gestational hypertension (GH, new hypertension after 20 weeks of pregnancy without proteinuria), and preeclampsia (PE, new hypertension with proteinuria and/or other organ dysfunction). GH and PE have estimated prevalence rates of 1.8–4.4 %, and 0.2–9.2 %, respectively (Umesawa and Kobashi, 2016), although some authors proposed a higher prevalence up to 8 % for the latter (Duley, 2009). HDP, and in particular PE, significantly increase the risk of severe perinatal complications for both mother and child, such as long-term maternal health issues like hypertension, ischemic heart disease, and stroke, as well as increased risk of recurrent HDP in future pregnancies (Chappell et al., 2021; Marschner et al., 2023; Steegers et al., 2010; Wu et al., 2017). HDP also raises the risks of preterm birth, stillbirth, intrauterine growth restriction, and the need for neonatal intensive care. Offspring are at higher risk of mortality due to perinatal diseases, cardiovascular diseases, and metabolic disorders later in life (Chappell et al., 2021; Marschner et al., 2023; Steegers et al., 2010; Turbeville and Sasser, 2020).

Growing evidence suggests a link between ambient air pollution and adverse pregnancy outcomes, including HDP. A National Toxicology Program (NTP) panel in the US concluded that exposure to traffic-related air pollution, especially PM with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) and nitrogen dioxide (NO_2), is presumed to be a hazard for developing HDP based on moderate evidence (Beverly et al., 2019). Associations with PM with aerodynamic diameter less than 10 μm (PM_{10}) have been reported in studies from Sweden and the Netherlands (Mandakh et al., 2020; Van Den Hooven et al., 2011), while $PM_{2.5}$ was examined by a greater number of studies, as recently reviewed (Bearblock et al., 2021). A recent investigation (Pedersen et al., 2024) examined the relationship between air pollution and HDP in Rome, Italy, suggesting a potential link between long-term exposure to multiple atmospheric pollutants, including PM_{10}, and various HDP subtypes.

In 2020, Italy had 40 incineration plants, primarily situated in the northern regions of the country (ISPRA, 2022). Lazio Region (central Italy) comprises two WTE plants, with one having been deactivated in recent years.

The overarching aim of this study is to assess the effect of maternal residential exposure to a municipal WTE plant in Lazio Region on the occurrence of adverse birth outcomes and hypertensive disorders of pregnancy. To reach this goal, a quasi-experimental study design is adopted: the analysis focuses on the temporal changes in these outcomes associated with the plant's operational status. We chose to employ a difference-in-differences design, comparing the rates of adverse events before and after the plant's closure to those observed during the same period in the vicinity of another WTE plant that, instead, remained operational.

2. Methods

2.1. Study area

The Colleferro WTE industrial complex spans about 30,000 square meters and includes two plants, the first of which began operations in December 2002, followed by the second in June 2003. It had an authorized capacity of 334 tons per day of refuse-derived fuel. In 2009 the incinerator had been seized for a few months due to its involvement in illegal waste disposal activities, triggering concerns and protestations by local communities (https://www.romatoday.it/zone/castelli/albano/albano-dopo-il-sequestro-di-colleferro-si-riaccende-la-protesta-contro-l-inceneritore.html.). The plant became then operational again and, since early 2017, the two treatment lines were deactivated before a revamping project, which was planned, could be executed. By late 2018, the Lazio regional government officially decided to close the plant and repurpose it as an industrial facility using mechanical-biological treatment (MBT) to improve the environmental sustainability of waste processing.

Colleferro area is situated in the River Sacco Valley, an environmentally critical area in Lazio Region due to its topography and the presence of multiple pollution sources, such as industrial facilities (among which a cement factory located near the WTE plant), highways, heavily trafficked roads, and biomass-based domestic heating.

According to previous research conducted in the same setting (Golini et al., 2014), we defined a 7-km buffer around the plant to identify the affected population. In sensitivity analyses, we expanded the buffers to 11 or 20 km, as detailed later.

The San Vittore del Lazio WTE plant spans approximately 50,000 m^2 and was operative since August 2002. Its authorized capacity was 304 tons per day of refuse-derived fuel. In recent years a revamping project was planned in order to improve the sustainability of the plant's activity and to increase the amount of treated waste. It was used as control area because it is quite close to the Colleferro WTE plant (<100 km), in the same region (Lazio), therefore we assume that temporal patterns in the outcomes observed here might serve as suitable counterfactual trends for Colleferro plant, in absence of closure. Specifically, the residents within 7 km from San Vittore del Lazio plant were used as a comparison group in the main analysis. In sensitivity analyses, we extended the buffer to 11 km.

2.2. Study population and health data

Study population was defined as all mothers with a geocoded residential address in the two study areas between 2007 and 2023. Information was derived from the Birth Assistance Certificate (*Certificato di Assistenza al Parto,* CeDAP), part of the Regional Health Information Systems which includes both mother- and newborn-related variables. We considered key variables related to the mother, including age at delivery, gestational age (defined accordingly to ultrasound scans and the date of birth), number of previous children, and educational level, as well as child-specific variables, such as birth weight, birth order, and ICD-9 diagnosis recorded at delivery. Following previous research (Pedersen et al., 2024), the date of conception was calculated by adding

14 days to gestational age duration.

Specifically, we defined the following adverse birth outcomes.

- Low birth weight: birth at weight less than 2500 g.
- Small for gestational age (SGA): weight at birth in grams located in the lowest 10th percentile for that gestational week and for the same sex. Due to the lack of reliable Italian or European intrauterine growth curves, as similarly done in previous research (Kramer et al., 2001), we used Canadian curves.
- Congenital anomalies: ICD-9 codes ranging from 740 to 759.
- Cardiac malformations: ICD-9 codes ranging from 745 to 747.
- Preterm birth: gestational age less than 37 weeks.

From the hospital discharge database (HDD), we linked information related to any maternal hospitalizations for hypertensive disorders of pregnancy.

Specifically, we defined HDP outcomes as follows, according to the ICD-9 classification.

- Hypertensive disorders of pregnancy (HDP): 642.3, 642.4, 642.5, 642.6, 642.7.
- Preeclampsia (PE): 642.4, 642.5, 642,6, 642.7.

Maternal residential addresses were geocoded using a previously established procedure (Mataloni et al., 2022). This enabled the individual attribution of socio-economic position at the time of delivery, based on a 5-level indicator developed at census block level, as detailed elsewhere (Cesaroni et al., 2006; Rosano et al., 2020).

In cases in which the residential address changed during pregnancy, we computed the average socio-economic position for each address to obtain a single value for each delivery. Since geocoded addresses were available only after December 31, 2006, we restricted the analysis after this period, despite the plant being operational since 2003. This approach was also helpful to prevent the wrong retrospective attribution of residential addresses to mothers who delivered before 2007, which could introduce bias.

2.3. Environmental covariates

Geocoding of maternal residence addresses enabled us to define a three-level variable that categorized the distance from industrial facilities present in the study areas, excluding the WTE plants, into three groups: <1 km, 1–2 km, and >2 km. This variable was included in the models as a confounder, to better estimate the specific effect of the WTE plant, while controlling from other sources of industrial pollution.

2.4. Statistical analysis

Our main objective was to evaluate the effect of Colleferro plant's closure on the selected health outcomes risk. To achieve this, we introduced an interaction term between a "pre-post" dummy variable (coded as 0 for deliveries between January 1, 2007 and January 31, 2017, and 1 for deliveries between February 1, 2017 and December 31, 2023) and a binary variable representing the WTE plant (Colleferro or San Vittore) associated with each delivery.

Specifically, we conducted a 2x2 difference-in-differences (DiD) analysis, a quasi-experimental method that allows for the assessment of changes over time in a "treated" group by comparing with an "untreated" group, which did not experience the same change across the two periods (Nianogo et al., 2023; Dimick and Ryan, 2014; Wing et al., 2018; Huepenbecker et al., 2022).

This approach allowed us to evaluate whether the changes from one operational period to another differed between the two areas, thereby determining if the closure of the Colleferro WTE plant influenced the risk of the outcomes, compared to the rates observed in the San Vittore area, where the plant remained operational.

One of the key assumptions of this approach is that, in the pre-closure periods, the outcome rates in the two study areas followed approximately parallel trends. In order to verify this, we plotted the area-specific rates of adverse outcomes across the two periods by trimester (visual inspection) and tested the parallel trend assumption by performing a logistic regression model on the trimester-specific rates for each outcome, with the study area as the main exposure. A p-value >0.05 indicated no statistically significant association between the study area and temporal patterns in the outcome occurrence, thus supporting the parallel trend assumption.

The primary analysis was based on the DiD model for residents within a 7 km radius from either the Colleferro or San Vittore WTE plants.

We conducted three sensitivity analyses: a) we repeated the main model but using 11 km buffers (instead of 7) from the plants; b) we restricted the analysis to the Colleferro area only, and we conducted a DiD analysis comparing residents within 7 km against those residing between 7 and 20 km, under the assumption that the latter were not affected by the plant closure, therefore they might serve as a suitable counterfactual surrogate; c) we repeated the latter approach but using a threshold of 11 km to distinguish exposed and unexposed individuals.

For every stage, models were adjusted for maternal age at delivery, number of previous children, maternal citizenship (Italian/foreign), sex of the newborn (as in previous literature a differential expression of birth defects by sex was shown (Lary and Paulozzi, 2001; Michalski et al., 2015)), maternal SEP at residence address and distance from other industrial plants (<1 km, 1–2 km, >2 km). Results are presented as odds ratios with 95 % confidence intervals [OR (95 % CI)].

3. Results

Table 1 presents the characteristics of the study population. A total of 25,360 deliveries occurred in the areas surrounding the Colleferro and San Vittore WTE plants during the study period. The median maternal age was approximately 32.5 years. In the Colleferro area, most mothers (39 %) had a medium-low socioeconomic status, while in the San Vittore area, most participants (22 %) had a medium-high status. Primiparity was common in both areas, with 51 % of mothers in Colleferro and 61 % in San Vittore being first-time mothers. Preterm birth and small for gestational age (SGA) were the most frequent outcomes. In the Colleferro area, preterm births occurred in 17 % of cases, and 14 % of newborns were classified as SGA. Similarly, in the San Vittore area, preterm births accounted for 15 %, and 13 % of infants were SGA. Hypertensive disorders of pregnancy (HDP) were observed in 2.3 % of deliveries in Colleferro and 1.7 % in San Vittore.

Fig. 1 shows a map of the study area with maternal residence addresses and the exposure zones categorized by distance from the WTE plant. Most of the study population lived in medium- or short-distance buffers. To protect participants' privacy, each address was randomly displaced within a 200 m buffer before being plotted on the map.

Fig. 2 displays the rates of adverse birth outcomes and HDP before and after the closure of the Colleferro WTE plant, stratified by maternal residence area. Except for cardiac malformations, significant differences in the change in rates between the two study periods are visually evident for all selected outcomes. Specifically, rates of small for gestational age, congenital anomalies, and pre-eclampsia decreased in the Colleferro area, while they increased in the San Vittore area. Both preterm birth and HDP rates increased in both areas, with a more pronounced increase observed in the San Vittore area. In contrast, the rate of low birth weight increased more substantially in the Colleferro area compared to the San Vittore area.

Fig. S1 presents time series for the selected outcomes, using trimester as time unit, to provide a clearer view of the progression of rates throughout the study period.

Table 2 displays the results of the controlled pre-post analysis with the difference-in-differences design. The parallel trend assumption was

Table 1
Maternal and delivery characteristics, stratified by distance from each WTE plant.

Characteristic	Colleferro			San Vittore		
	Overall, N = 19,929[a]	≤=7 km, N = 5,635[a]	>7 km, N = 14,294[a]	Overall, N = 5,431[a]	≤=7 km, N = 2,180[a]	>7 km, N = 3,251[a]
Maternal age	32.6 (29.0, 36.1)	32.9 (29.2, 36.2)	32.5 (28.9, 36.1)	32.7 (28.8, 36.2)	32.3 (28.5, 35.9)	33.0 (29.0, 36.4)
Maternal citizenship						
Italian	17,538 (88 %)	4879 (87 %)	12,659 (89 %)	5266 (97 %)	2120 (97 %)	3146 (97 %)
Foreign	2391 (12 %)	756 (13 %)	1635 (11 %)	165 (3.0 %)	60 (2.8 %)	105 (3.2 %)
Maternal Socio-economic position						
High	667 (3.3 %)	89 (1.6 %)	578 (4.0 %)	823 (15 %)	345 (16 %)	478 (15 %)
Medium-High	2877 (14 %)	1021 (18 %)	1856 (13 %)	1247 (23 %)	774 (36 %)	473 (15 %)
Medium	5419 (27 %)	1771 (31 %)	3648 (26 %)	1207 (22 %)	365 (17 %)	842 (26 %)
Medium-Low	7785 (39 %)	2170 (39 %)	5615 (39 %)	1030 (19 %)	337 (15 %)	693 (21 %)
Low	3181 (16 %)	584 (10 %)	2597 (18 %)	1124 (21 %)	359 (16 %)	765 (24 %)
Distance from other industrial plants						
>2 km	16,561 (83 %)	2915 (52 %)	13,646 (95 %)	3761 (69 %)	1934 (89 %)	1827 (56 %)
1–2 km	852 (4.3 %)	660 (12 %)	192 (1.3 %)	264 (4.9 %)	25 (1.1 %)	239 (7.4 %)
<1 km	2516 (13 %)	2060 (37 %)	456 (3.2 %)	1406 (26 %)	221 (10 %)	1185 (36 %)
Gestational age	39.00 (38.00, 40.00)	39.00 (38.00, 40.00)	39.00 (38.00, 40.00)	39.00 (38.00, 40.00)	39.00 (38.00, 40.00)	39.00 (38.00, 40.00)
Number of previous pregnancies						
0	10,173 (51 %)	2881 (51 %)	7292 (51 %)	3332 (61 %)	1327 (61 %)	2005 (62 %)
1	6053 (30 %)	1758 (31 %)	4295 (30 %)	1295 (24 %)	548 (25 %)	747 (23 %)
2	2411 (12 %)	659 (12 %)	1752 (12 %)	544 (10 %)	211 (9.7 %)	333 (10 %)
3+	1292 (6.5 %)	337 (6.0 %)	955 (6.7 %)	260 (4.8 %)	94 (4.3 %)	166 (5.1 %)
Sex of the newborn						
Males	10,283 (52 %)	2893 (51 %)	7390 (52 %)	2780 (51 %)	1122 (51 %)	1658 (51 %)
Females	9644 (48 %)	2742 (49 %)	6902 (48 %)	2647 (49 %)	1057 (48 %)	1590 (49 %)
Weight at birth	3230 (2,940, 3530)	3238 (2,935, 3540)	3230 (2,940, 3526)	3280 (2,980, 3580)	3270 (2,978, 3570)	3290 (2,980, 3590)
Low birth weight (<2500 g)	1479 (7.4 %)	398 (7.1 %)	1081 (7.6 %)	360 (6.6 %)	156 (7.2 %)	204 (6.3 %)
Small for gestational age	2838 (14 %)	758 (13 %)	2080 (15 %)	699 (13 %)	286 (13 %)	413 (13 %)
Congenital anomalies	1236 (6.2 %)	341 (6.1 %)	895 (6.3 %)	261 (4.8 %)	122 (5.6 %)	139 (4.3 %)
Cardiac malformations	600 (3.0 %)	172 (3.1 %)	428 (3.0 %)	102 (1.9 %)	48 (2.2 %)	54 (1.7 %)
Preterm birth (<37 weeks)	3358 (17 %)	980 (17 %)	2378 (17 %)	790 (15 %)	326 (15 %)	464 (14 %)
Preeclampsia	191 (1.0 %)	56 (1.0 %)	135 (0.9 %)	67 (1.2 %)	26 (1.2 %)	41 (1.3 %)
Hypertensive disorders of pregnancy	455 (2.3 %)	125 (2.2 %)	330 (2.3 %)	90 (1.7 %)	37 (1.7 %)	53 (1.6 %)

[a] Median (IQR); n (%).

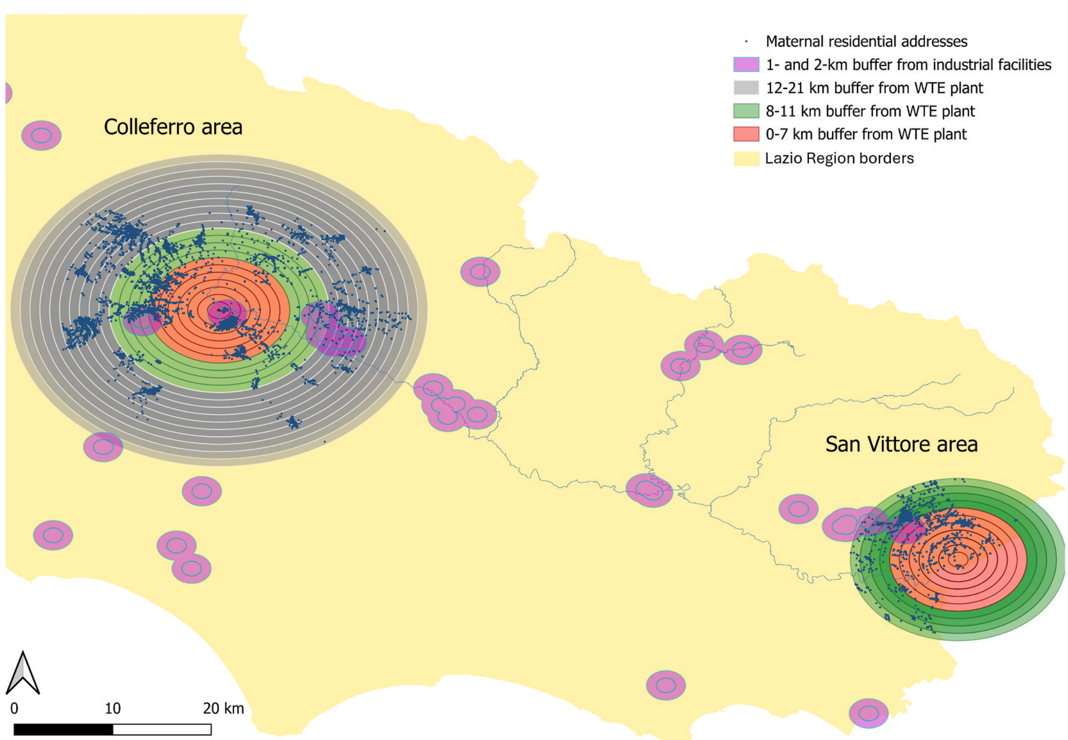

Fig. 1. Study areas, geocoded maternal addresses, other industrial facilities.

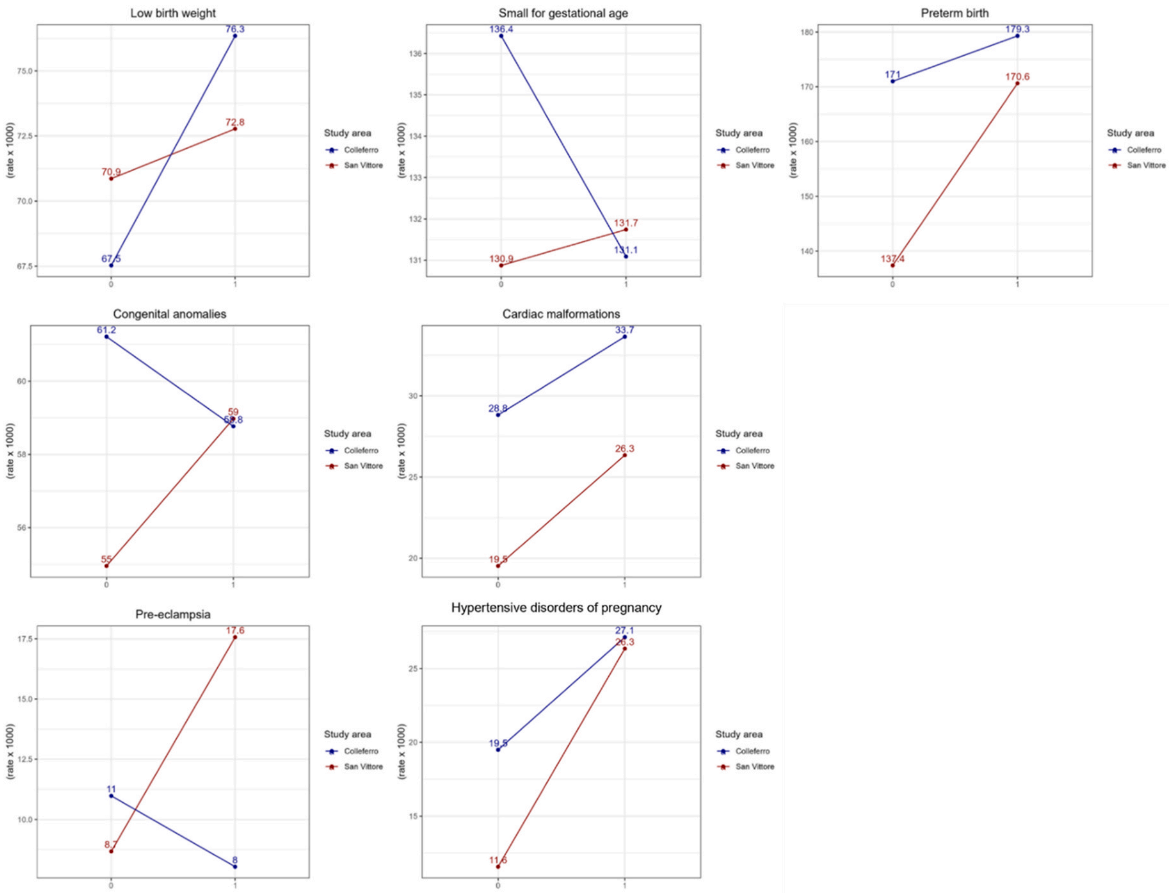

Fig. 2. Rates of adverse birth outcomes and HDP before and after the closure of the Colleferro WTE plant, stratified by maternal residence area.

Table 2
Controlled pre-post analysis conducted within a 7 km buffer around the Colleferro and San Vittore WTE plants. Results for the interaction term between maternal residence area and period of delivery (pre-/post-closure of the Colleferro plant) are shown, with the San Vittore area as the reference group. Results are expressed as odds ratios with 95 % confidence intervals [OR (95 % CI)].

	N (Colleferro)	N (San Vittore)	OR (95 % CI)
Low birth weight (<2500 g)	398	156	1.12 (0.75–1.67)
Small for gestational age	758	286	0.95 (0.70–1.29)
Congenital anomalies	341	122	0.89 (0.57–1.38)
Cardiac malformations	172	48	0.86 (0.45–1.66)
Preterm birth (<37 weeks)	980	326	0.83 (0.62–1.10)
Pre-eclampsia	56	26	0.35 (0.13–0.93)
Hypertensive disorders of pregnancy	125	37	0.61 (0.29–1.30)

tested for each analyzed outcome and results displayed a p-value >0.05 for all outcomes (data not shown). We found that mothers residing in a 7 km buffer from Colleferro WTE plant had a 65 % reduction in the risk of pre-eclampsia during the plant's closure period, compared to when the plant was operational, in contrast to study participants from San Vittore area (0.35; 0.13–0.93). Point estimates for the other outcomes, except for low birth weight, also indicated a similar reduction in risk in Colleferro, although none of these results reached statistical significance. The reduction in pre-eclampsia risk remained statistically significant when considering an 11 km buffer around each plant, as shown in Table S1. However, no statistically significant results were found when focusing only on Colleferro area and considering subjects outside the exposure buffer as the comparison group, as shown in Table S2.

4. Discussion

A reduction in risk of pre-eclampsia was observed during the post-operational period of the Colleferro WTE plant, compared to the San Vittore area where the facility remained active. Other outcomes showed a similar trend of risk reduction based on point estimates, although statistical significance was not reached for these.

In contrast, the San Vittore area exhibited increased rates for all studied outcomes moving from one period to the subsequent. A possible explanation is that, following the deactivation of the Colleferro plant, waste disposal activities were redirected to the San Vittore plant, leading to higher emissions and potentially greater health impacts on the local population.

The association between prenatal exposure to waste incineration facilities and adverse birth outcomes was previously analyzed in several studies with systematic reviews summarizing the findings (Ashworth et al., 2014; Vinti et al., 2021; Negri et al., 2020).

For example, several studies have investigated the link between waste processing and congenital anomalies (Vinceti et al., 2008, 2009, 2018; Cordier et al., 2004, 2010; Cresswell et al., 2003). A retrospective cohort study in England and Scotland (Parkes et al., 2020) found a 4 % increase in the risk of cardiac malformations associated to PM_{10} emissions from a municipal waste incinerator.

Another similar study conducted in the same region over a 37-year period (Dummer et al., 2003) reported a 12 % increase in the risk of cardiac anomalies related to maternal residential proximity to an incinerator. However, other studies, including those conducted in Italy, did not find increased risks for congenital anomalies associated with waste incineration activities (Vinceti et al., 2008, 2009, 2018).

Regarding preterm birth and small-for-gestational-age, some studies

(Ghosh et al., 2019; Lin et al., 2006; Tango et al., 2004; Santoro et al., 2016) were unable to detect significant effects, while an Italian multisite study (Candela et al., 2013) reported a 30 % increase in risk associated to the highest quintile of PM_{10} exposure from a municipal waste incinerator.

Recent research on pre-eclampsia have found significant associations between PM exposure during pregnancy and the occurrence of this adverse outcome. For instance, a Swedish study (Mandakh et al., 2020) found a 43 % increase in risk associated with exposure to the highest quartile of PM_{10} during pregnancy compared to the lowest quartile, and a 40 % increase for the highest quartile of $PM_{2.5}$.

A study in the Netherlands (Van Den Hooven et al., 2011) also found a 72 % increase in the risk of pregnancy-induced hypertension related to PM_{10} exposure. Similarly, a Spanish study (Dadvand et al., 2013) found a 32 % increase in risk for each 5 $\mu g/m^3$ increase in $PM_{2.5}$ exposure during pregnancy, while a California-based study (Wu et al., 2009) reported a 32 % higher risk for each 1 $\mu g/m^3$ increase of the same pollutant.

Our findings, despite limited statistical significance, support the hypothesis that the WTE plant that we considered may have had a plausible effect on adverse birth and pregnancy outcomes. However, further research involving a larger population would be necessary for clearer insights. It is worth noting that very few studies have reported significant associations in similar settings. Nevertheless, we did observe a significant difference in the change in pre-eclampsia rates between the Colleferro and San Vittore areas, with Colleferro experiencing a greater reduction in pre-eclampsia rates following the closure of the WTE plant.

As recently reviewed (Fussell et al., 2024), prenatal exposure to air pollution can contribute to adverse birth outcomes through several biological mechanisms. Pollutants may affect placental vasculature, causing endothelial dysfunction and vasoconstriction, which are linked to preterm birth and abnormal fetal growth. During placentation, trophoblastic cells transform maternal arteries into low-resistance vessels that regulate oxygenated blood flow to the placenta. Disruptions in this process can lead to hyperoxia or fluctuating oxygen levels, contributing to complications like miscarriage, pre-eclampsia, and fetal growth restriction (FGR). Chronic placental malperfusion increases oxidative stress, damaging biomolecules and interfering with critical signaling pathways.

Air pollutants can also induce proinflammatory responses that disturb the balance between pro- and anti-inflammatory states, potentially leading to adverse outcomes. Preterm birth, for example, is often associated with early inflammation, marked by cytokine activation. Inflammation can impair placental function, leading to FGR and other fetal developmental issues. Additionally, reduced DNA methylation due to PM exposure and down-regulation of LINE-1 may further contribute to these negative effects.

Regarding pre-eclampsia, as noted in previous reviews (Bearblock et al., 2021), women who experience this condition during pregnancy are at higher risk of developing hypertension later in life, suggesting a potential predisposition to hypertension. $PM_{2.5}$ exposure has been associated with endothelial dysfunction, which leads to reduced flow-mediated dilation. A decrease of 0.3 % in flow-mediated dilation has been reported for every 3 $\mu g/m^3$ increase in the annual average of $PM_{2.5}$ exposure. This endothelial impairment may predispose individuals to hypertension, and the physiological stress of pregnancy could trigger the development of pre-eclampsia.

This study has several strengths. The availability of two WTE plants—one deactivated and the other remaining active—provided a "natural experiment" framework, allowing us to apply a “difference-in-differences” (DiD) design. This approach was used to compare the effects of the WTE plant’s closure over time by analyzing two groups: the “treated” group (Colleferro) and the control group (San Vittore). These groups were distributed across similarly sized spatial buffers and distanced less than 100 km from one another, ensuring comparable geographic zones for analysis. This approach allowed for the assessment of both the direct impacts of the plant’s operation (or closure) on health outcomes, as well as indirect effects, such as increased environmental concerns and stress due to years of protests against WTE and media coverage, which could affect health even if pollutant exposure decreased after the closure.

By considering the San Vittore area a counterfactual, we could simulate what the situation in Colleferro might have been if the WTE plant had not closed.

The DiD approach was used in previous studies conducted in similar settings (Legrande et al., 2019), providing the advantage of removing both known and unknown confounding “by design” because it compares the rate of event across the same population groups over time.

Geocoding of maternal residence addresses enabled individual exposure assessments and the inclusion of important covariates, such as SEP and proximity to other industrial plants. Moreover, the accuracy and comprehensiveness of data from Regional Informative Systems enabled the inclusion of multiple covariates in the statistical analysis. To the best of our knowledge, this is the first study to examine the potential effect of waste incineration on HDP, particularly in the context of a facility’s closure.

Despite its strengths, this study also has several limitations. The rarity of most studied outcomes may have limited the ability to detect an effect of the WTE plants on adverse outcomes under study. Moreover, information about part of the population living within the San Vittore buffer was unavailable due to the plant’s location near the border between Lazio and Campania regions, which resulted in the unavailability of data for residents outside Lazio region. Undocumented periods during which the Colleferro plant was not operational may have introduced bias into the analysis. The date January 31, 2017 was selected as the cut-off between the two study periods, based on local information sources suggesting that the plant ceased operations by the end of January 2017. However, the exact shutdown date remains unknown. The use of ICD-9 codes for outcome classification might have introduced bias, though we attempted to mitigate this including secondary diagnoses. Additionally, data from the birth defects registry was not available for the present study, then caution should be applied when considering the results for congenital anomalies, which were obtained solely from the ICD-9 codes which characterized the newborns’ hospital admissions as listed in the birth certificate. Future analyses could benefit from a more granular classification of the outcomes studied, considering that, regarding hypertensive disorders of pregnancy outcomes, the various codes often refer to different variants of the same pathology.

Additionally, the two population subgroups may have differed in ways not fully accounted for and a complex environmental context in the Colleferro area, which could have affected the observed risks.

In facts, it is worth noting that the DiD analysis using the San Vittore area as the control is the only approach that displayed statistically significant results, unlike the DiD that used as reference the outer area of Colleferro (up to 20 km from the plant), which instead did not reveal significant effects. This lack of significant findings in the latter case can presumably be attributed to the fact that when the DiD approach was applied using the outer ring as the comparison area, the smaller observed differences attributed to the plant’s closure might be influenced by other environmental issues present in the outer ring (such as other industrial facilities), which might also have an impact on the same health conditions under study.

Unlike previous studies conducted in the same area that used dispersion models for individual exposure assessment (Golini et al., 2014), we opted to use distance as a proxy for maternal exposure to emissions from the WTE plants. Distance was deemed more suitable for this study, as it allowed us to capture not only the direct effects of emissions but also the indirect impacts associated with the presence of the plants, such as stress and concerns among residents. These psychological effects were particularly relevant in the case of the Colleferro plant, where strong protests ultimately led to the closure of the facility. Moreover, dispersion models were developed at the time of the plants’ activation in 2003, and their inclusion could have introduced additional bias. Nonetheless, the choice of distance-based exposure assessment, combined with the small population size, may have contributed to the lack of statistical significance observed in the analysis.

5. Conclusion

In this study we observed a reduction in the risk of pre-eclampsia following the closure of Colleferro WTE plant, using San Vittore area, where the WTE plant remained active, as a comparison. Further research is needed to expand on these results, using a broader population as the control group and mitigating the risk of bias rising from potential residual confounding. A better assessment of the potential confounding effect due to the presence of other industrial facilities in the area might account for the specific type of facilities and their operating periods. Additionally, background air pollution from adequate dispersion models could serve as an adjustment variable. Future research may also consider dispersion models for exposure assessment.

While further investigation is necessary to better quantify the risks, our results suggest that prenatal exposure to emissions from WTE plants could pose potential risks to both maternal and neonatal health, particularly due to the clinical implications of pre-eclampsia. Women who develop pre-eclampsia during pregnancy are at an increased risk of developing hypertension later in life. From a public health perspective, it is essential to implement stricter environmental regulations to limit air pollution, enforce more stringent monitoring of emissions, and encourage the adoption of cleaner technologies that reduce harmful byproducts. In addition, improving waste management practices, such as increasing recycling rates, reducing waste generation, and transitioning to sustainable disposal methods, can significantly lessen the environmental impact of waste incineration. This multi-faceted strategy may not only help protect maternal, fetal, and neonatal health but also contribute to a cleaner, healthier environment for future generations. The concerns of communities living around incineration plants also highlight the need for public health surveillance, particularly for vulnerable population subgroups such as pregnant women.

CRediT authorship contribution statement

Alessandro Trentalange: Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Isabella Bottini:** Writing – review & editing, Conceptualization. **Massimo Stafoggia:** Writing – review & editing, Resources, Methodology, Conceptualization. **Paola Michelozzi:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Carla Ancona:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Funding

This study was conducted as part of the “One Health Citizen Science” project, funded by the Italian Ministry of Health (PNC PREV-A-2022-12377005).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was conducted within the Epidemiology Master Programme at Turin University. Authors would like to thank the scientific committee for their support. Sincere thanks also to Lisa Bauleo and Francesco Forastiere.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.121926.

Data availability

The authors do not have permission to share data.

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