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Faculty of Medicine, Institute of Family Medicine and Public Health,
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II Idavain, J., Julge, K., Rebane, T., Lang, A., Orru, H., 2019. Respiratory symptoms, asthma, and levels of fractional exhaled nitric oxide in schoolchildren in the industrial areas of Estonia. Science of the Total Environment 650, 65−72. DOI: 10.1016/j.scitotenv.2018.08.391

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The contribution of Jane Idavain to the original publications:

In Paper I the author collected the data and actively participated in interpreting the results and writing the manuscript.

In Papers II and III, the author participated in formulating the research questions, collected and analysed the data, interpreted the results, and wrote the manuscripts as the first author.

ABBREVIATIONS

ASIR	age-standardised incidence rate
BMI	body mass index
CO	carbon oxide
CO_2	carbon dioxide
COPD	chronic obstructive pulmonary disease
EU	European Union
EC	European Commission
HC	hydrocarbons
HIA	health impact assessment
IARC	the International Agency for Research on Cancer
NO_2	nitrogen dioxide
O_3	ozone
PAHs	polycyclic aromatic hydrocarbons
$PM_{2.5}$	fine particles, particles with diameter below 2.5 µm or less
PM_{10}	particles, particles with diameter below 10 µm or less
SINPHONIE	Schools Indoor Pollution and Health: Observatory Network in Europe
SO_2	sulphur dioxide
SOHOS	Studies Of the Health impact of Oil shale Sector
VOCs	volatile organic compounds

1. INTRODUCTION

Industrially contaminated areas often have high concentrations of air pollution and other environmental pollutants, which can cause increased morbidity and mortality (Martuzzi et al., 2014). In addition to direct health effects caused by industrial exposure, there are indirect health effects like the perception of low environmental quality that may cause constant annoyance and discontentment (Kosteska and Topuzovska-Latkovic, 2022).

Since the beginning of the 20th century, Ida-Viru County in North-East Estonia has been the main industrial area of the country, concentrating on oil shale production. Oil shale is an organic-rich sedimentary rock containing kerogen that has been mined and excavated there and used for electricity generation and shale oil extraction in the chemical industry (Vaimann and Risthein, 2018).

The usage of oil shale was most significant during the 1980s when the production was up to 30 million tonnes per year. Thereafter, excavation volumes gradually decreased after the nearby Leningrad nuclear power plant near Saint Petersburg started operating and decreasing electricity export to Russia (Gavrilova et al., 2005) and after the collapse of the Soviet Union. The excavation of oil shale decreased until 1999 to ~9.5 million tonnes per year, increasing to nearly 16 million tonnes per year until 2018. (Habicht, 1994; TalTech Virumaa kolledži põlevkivi kompetentsikeskus, 2019). Afterwards, it decreased again and, in recent years, has remained at around 10 million tonnes per year (TalTech Virumaa kolledži põlevkivi kompetentsikeskus, 2023).

While the oil shale industry employed 7,300 people in 2017, being relatively large employer in the region (TalTech Virumaa kolledži põlevkivi kompetentsikeskus, 2018), in recent years, the number of employed in the oil shale industry has decreased to 5,600 people (TalTech Virumaa kolledži põlevkivi kompetentsikeskus, 2023).

Ida-Viru County is the third largest region in Estonia after Harju County (the capital region in the Northen-Estonia) and Tartu County (a biggest region in Southern-Estonia). The Gulf of Finland borders the region to the north, the Narva River and Russia to the east, and Lake Peipus to the south. Its population is around 132,000 people and has decreased tremendously since 2000, when its population was ~183,000 people (Statistics Estonia, 2024). The population structure is more inclined towards the elderly.

Life expectancy estimates are a core indicator of society's health and well-being. Average life expectancy at birth is the most widely used measure of population health. In the last twenty years, life expectancy in Estonia has increased faster than the average in the European Union countries. By 2022, the gap in Estonia compared to the European Union average (80.6 years) had shrunk to one year for women and four years for men (Eurostat, 2022a).

Life expectancy is still the lowest in Ida-Viru County compared to other counties, falling around two years short of Estonian average (Statistics Estonia, 2022a). The level of education has a significant impact on life expectancy.

According to Statistics Estonia, in 2021, a person with a higher education lived eleven years longer in Estonia than a person with a basic education. The proportion of higher education among residents in Ida-Viru County in 2021 was 3% less than the average in Estonia (36%) (Statistics Estonia, 2022b).

People's general perception of their good health gives an insight not only to the absence of disease or injury but also to physical, mental, and social well-being. Europe's perception of good and very good health has remained at an average of 67–68 % since 2010. In Estonia, only 52% of the people perceived their health as very good or good in 2010 and 58% in 2022 (Eurostat, 2022b). Additionally, in Ida-Viru County, its residents perceive their health worse than the rest of Estonia. Only 42% of its people consider their health and well-being good in 2021 (Statistics Estonia, 2022c). The gap between Estonia's average is 10% points, and the EU average is more than 20% points.

Healthy life expectancy at birth is another important indicator for assessing the population's health. It signals strongly whether or not our last years are lived in good health. The average number of healthy life years at birth in the EU was 63.6 years in 2021. This number has evolved by 1.8 between 2010 and 2021, rising from 61.8 healthy years to 63.6 (Eurostat, 2021). At the same time, the average healthy life expectancy at birth in Estonia has remained about 7 years lower than the EU average for the past eleven years, standing at 56.7 years. In Ida-Viru County, the average healthy life expectancy is even lower, by 4 years compared to the national average, and over 10 years lower than the EU average. The gap between the EU and Ida-Viru County has increased from 7 years in 2010 to 11 years in 2021 (Statistics Estonia, 2021).

Long-term exposure to air pollution and industrial contaminants is responsible for increased morbidity and mortality due to cardiovascular diseases (Bai et al., 2018; Rajagopalan et al., 2018; Shah et al., 2013). Mortality due to cardiovascular diseases during two decades has been 20% higher in Ida-Viru County than average in Estonia, both for males and females (Tervise Arengu Instituut, 2023). The difference from the Estonian average was lowest in 2007 (8,2% higher) and highest in 2016 (30% higher), starting to decrease. Short-term exposure to air pollution can cause and aggravate multiple respiratory conditions, including asthma, bronchitis, and chronic obstructive pulmonary disease (COPD). Morbidity to asthma has been around two per cent higher for years in Ida-Viru County than average in Estonia (Vasar et al., 2011; Этлин, 1989).

Cancer is another serious illness linked to industrial pollution (IARC, 2012). Cancer morbidity in Estonia has been above the EU average for men but below the average for women in recent years (OECD/European Commission, 2025). Cancer morbidity (except skin cancer (other)) in Ida-Viru County has increased since 2010 and since then remained 15% higher than the Estonian average (Tervise Arengu Instituut, 2024a). Conversely, cancer mortality in Ida-Viru County has been at or slightly below the national average for many years but has started to increase since 2020 (Tervise Arengu Instituut, 2024b).

The public's perception and expectation of environmental quality have significantly increased in recent decades. Thoughtful and deliberate integration of structures and operations into the natural surroundings is crucial in today's society. Effective addressing of any form of pollution – including air pollution, noise pollution, water contamination, or land degradation – is of principal importance. Industrially contaminated areas have long experienced an additional burden on the environment, consequently affecting health and well-being.

2. REVIEW OF THE LITERATURE

2.1 Environmental pollution and its effects on health

Environmental pollution is the result of the emission of pollutants into the environment (air, water, soil) as a result of human activities, where it exceeds the natural content of a certain substance. Contaminants can easily cause instabilities and distortions in the environment and interfere with the normal functioning of organisms (including humans) and the environment. Depending on the environment into which the pollutant enters, air pollution, soil pollution, and water pollution can be distinguished (Moeller, 2011).

2.1.1 Air pollution and its effects on health

Air pollution is a complex mixture of fumes, gases and dust in quantities that could harm humans, animals, or ecosystems (Vallero, 2008). Pollutants which contribute to air pollution can be either primary or secondary. Primary pollutants are emitted directly into the air, like particulate matter (PM_{10}), fine particles ($PM_{2.5}$), soot or black carbon (BC), as well as gaseous pollutants such as carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOCs) from vehicles exhausts, wood burning and several industrial activities. Secondary pollutants are not emitted directly from the source but emerge when primary pollutants undergo a chemical reaction in the atmosphere. An example of acid rain is an alteration of the deposition of SO_2 or NO reaction with water or near-surface ozone (O_3), which is formed by the interaction of various compounds (VOCs, hydrocarbons (HC), nitrogen oxides (NO_x)) in the presence of sunlight (Boubel et al., 1994).

Air pollution can mainly occur in urban settings and industrial areas. In industrially polluted areas, many different harmful human health effects have been documented, such as increased morbidity and mortality rates, increased hospital admissions, and adverse reproductive outcomes (Ancona et al., 2015; Comba et al., 2014; Martuzzi et al., 2014; M. Pascal et al., 2013; Pasetto et al., 2012; Pirastu et al., 2013b; Rom et al., 1981).

Children's health

Air pollution can affect children at different times: before birth, shortly after birth and during a child's growth (Melody et al., 2019; Stieb et al., 2012). It has been shown that children are particularly sensitive to air pollution exposure, as their pulmonary metabolic capacity has not yet fully developed (Kurt et al., 2016). Exposure to air pollution can, therefore, adversely affect children's lung development (Rice et al., 2016). At the same time, in the early stages of a child's development, including foetal development, air pollutants can cause reproductive and developmental disorders like preterm deliveries and low birth weight (Deziel et al., 2020) as well as respiratory health problems (Vasar et al., 2011; Этлин, 1989).

Moreover, children living near (e.g. within 5 km) industrial sites or exposed to industrial pollutants have an increased risk of poorer health outcomes than those less exposed or living further away (e.g. >20 km) (Alwahaibi and Zeka, 2016; Bergstra et al., 2018; Dahal et al., 2022; De Sario et al., 2018; DeCicca and Malak, 2020; Lewin et al., 2013; Nirel et al., 2014; Smargiassi et al., 2014; Veber et al., 2022; Wichmann et al., 2008; Wilhelm et al., 2007; S. Wong et al., 2016; Yang et al., 1997).

In contrast, decreased exposure to air pollution has shown favourable effects on health outcomes among children. For instance, during the COVID-19 pandemic, when several industries were shut down, PM10, NO2, and SO2 levels in the air dropped significantly, leading to an average decrease in preterm births by 20% (Vaccaro et al., 2021) and increased birth weights by approximately 15% (Aix et al., 2022; Yalçin et al., 2022).

Respiratory health

Air pollution can harm the respiratory system either directly (e.g. airway inflammation) or indirectly (e.g. by altering its immune response) (Glencross et al., 2020). Susceptibility to air pollutants varies among individuals, but children, the elderly and pregnant women are more vulnerable than other people (Kurt et al., 2016; Rice et al., 2016; Sun and Zhu, 2019). Sociodemographic factors, comorbidities and genetics also impact a person's susceptibility to air pollution and could cause many respiratory outcomes, both acute and chronic. Regarding the time and duration of exposure, acute respiratory effects are associated with recent exposure (hours or days), whereas chronic diseases are often a result of constant exposure that is longer than six months (Rice et al., 2016).

Higher proportions of air pollutants within a short period also cause several acute respiratory effects, from mild irritations, inflammations, and allergic reactions to complete respiratory failures that might lead to increased numbers of emergency room visits, hospitalizations, and deaths (Bell et al., 2009; Brunekreef and Holgate, 2002; Rich et al., 2019; Samoli et al., 2016; Xia et al., 2017). However, long-time exposure to air pollutants has been indicated to have a direct relationship with developing chronic diseases like asthma and chronic obstructive pulmonary disease (COPD) (Adam et al., 2015; Anderson et al., 2012; Doiron et al., 2019; Jacquemin et al., 2012; Li et al., 2003; Zanobetti et al., 2008).

Cardiovascular health

Long-time exposure to air pollution and industrial contaminants is also responsible for increased morbidity and mortality due to cardiovascular diseases (Bai et al., 2018; Rajagopalan et al., 2018; Shah et al., 2013). Breathing poor-quality air, the nanosized particles migrate to tissues and organs, including arteries, damaging blood vessels by making them narrower and more complicated and making it more difficult for the blood to flow freely. Therefore, the blood might clot, increasing blood pressure as the heart needs to pump more often to move the blood that cannot flow properly (Abohashem et al., 2021). Air pollution also affects the heart's electrical system, which controls the heartbeat, causing arrhythmias (Al-Kindi et al., 2020). For people with existing cardiovascular conditions (especially older people), additional damage can increase their risk of events like a heart attack or stroke (Peralta et al., 2020; Rajagopalan and Landrigan, 2021). Therefore, populations exposed to higher levels of $PM_{2.5}$ have a significantly higher circulatory disease incidence and mortality rate. Several studies have indicated that particle pollution significantly affects blood pressure, shortness of breath, and the emergence of heart attack and stroke (Dehbi et al., 2017; Lee et al., 2014; Sepandi et al., 2021).

Malignant neoplasms

Long-term exposure to air pollutants has also been evidenced as a carcinogenic risk to human health (IARC, 2016). The strongest evidence of an effect on cancer is so far seen on lung cancer (Coleman et al., 2020; Hemminki and Pershagen, 1994; Lepeule et al., 2012; Pope Iii et al., 2002; Turner et al., 2016). Other types of cancer have also been directly or indirectly associated with airborne particles. However, the epidemiological evidence is still limited: for instance, some studies have reported positive associations with pancreatic cancer (Ancona et al., 2015), cervical cancer (Raaschou-Nielsen et al., 2011), breast cancer (C. M. Wong et al., 2016), kidney, bladder and colorectal (Turner et al., 2017) and liver cancer (Pedersen et al., 2017).

2.1.2 Other types of pollution and their effect on health

Besides air pollution, other types of pollution might affect health. Water bodies in large cities and agricultural and industrial regions are important, and therefore, people living in intensive agricultural or industrial areas are mainly vulnerable to contaminated and polluted water (UNECE, 1993). Pollutants like organic matter, acids, alkalis, nitrogen, phosphate, phenols, and heavy metals like lead, cadmium, mercury, and zinc are among the major hazardous substances found in the bodies of water near rural and industrial residential areas and in their drinking water systems (Eckenfelder, 1970; Salomons and Förstner, 2012). Even though most health-related diseases due to water pollution are connected to communicable diseases like typhoid fever, dysentery, cholera, etc. (Landrigan et al., 2018), constant use of contaminated and polluted water cause also non-communicable diseases like gastric ulcer, skin diseases, different neoplasms like bladder, breast and colon cancers (Halder and Islam, 2015; Jiang et al., 2022; Schwarzenbach et al., 2010).

Soil pollution is also a direct land contamination caused by industrial or agricultural activities. As a consequence of its occurrence in the land-to-atmosphere connection, the soil is also a recipient of various atmospheric pollutants. Industrially contaminated land can contain higher concentrations and a wider range of pollutants. Mines and fossil fuel combustions are the primary sources of land contamination by heavy metals like arsenic, copper, lead, cadmium, zinc, mercury, etc. (Harrison, 2001). Once contaminated due to heavy metals or other polluting agents, soil accumulates its residues for many years and poses a serious risk to environmental safety and human health. Heavy metal accumulation in human can cause several health effects – chronic arsenic poisoning is related to skin problems, including skin cancer, high blood pressure, and neurological dysfunctions (Chen et al., 2009; Chou and Harper, 2007). Higher portions of lead can cause irreversible changes in the central nervous system of the foetus during prenatal development and circulatory diseases, also cause kidney and liver dysfunctions (Abadin et al., 2020) and cadmium is carcinogenic, nefrotoxic, and neurotoxic, and can cause liver damage, circulatory diseases, skeletal disorders (Faroon et al., 2012).

In contrast to anthropogenic pollution, radon is a naturally occurring colourless, odourless, and tasteless radioactive gas that is formed by the disintegration of uranium. In the free atmosphere, radon is diluted by air and only reaches a low concentration; however, in a more concentrated areas, like underground mines, especially those containing uranium, radon can accumulate and reach high concentrations. (Keith et al., 2012). Indoor radon can also originate from groundwater and building materials. Initially, radon was thought to pose a threat only to miners, but indoor radon exposure's risk to the general population now well recognized (Darby et al., 2006; Krewski et al., 2005). Lung cancer is essentially the only health risk associated with higher proportions and long-time exposure to radon and the radon progeny (IARC, 1988; US Department of Health and Human Services, 2005). Several studies have indicated that radon is a strong occupational hazard especially for underground mine workers. Uranium, other metals, coal mines, also oil refineries and power plants are the primary source of radon related occupational exposure (Lane et al., 2010; Schnelzer et al., 2010; Smerhovsky et al., 2002; Tomášek et al., 1994; Vacquier et al., 2008). Estonia's radon emissions are high, among the highest in Europe (Petersell et al., 2015). The risk is highest in the Northern Estonian klint zone, where the radon concentration in the soil air exceeds the recommended limit value several times (Petersell et al., 2017a).

2.1.3 Annoyance and its effect on health

Annoyance caused by environmental contamination (e.g. air pollution) qualifies as a public health concern, as it can be seen as an outdoor stressor causing disturbance, stress and several diseases affecting the quality of life (Berglund et al., 1987). Annoyance caused by air pollution can mainly cause mental health problems (Hyslop, 2009; Yang et al., 2021). Perceived pollution and environmentally induced annoyance have been identified as useful signals for health symptoms in odorous environments at non-toxic levels of exposure (Claeson et al., 2013; Orru et al., 2018). Perception of air pollution is mainly based on visual and sensory implications and has been shown to mediate between environmental exposure and health (Oglesby et al., 2000). If the identified source is perceived as unpleasant, it is more likely to have a negative impact on health, e.g., evoke annoyance, worry, or disgust as an exacerbation mechanism (Kosteska and Topuzovska-Latkovic, 2022; Sucker et al., 2008). Another factor that may lead to annoyance, negative health symptoms, and possibly disease, is worry due to perceived health risks. The belief that a certain chemical/physical exposure is hazardous (irrespective of whether it is hazardous or not) and the worry and stress that it causes have been shown to contribute to mental as well as physical health symptoms (Claeson et al., 2013; Stenlund et al., 2009). This is likely explained by mechanisms such as stress-induced inflammation and expectations for a clean and safe environment. Aspects that also may modify annoyance include social status and the level of perceived control a person has over one's well-being. For example, people with a low level of education and members of minority groups (e.g. ethnic minorities like non-Estonians) can be more often annoyed (Lissåker et al., 2016; K. Orru et al., 2015). This kind of annoyance has also been explained by an inability to cope with risks related to one's physical or psychological well-being (Runeson-Broberg and Norbäck, 2013).

2.2 Industrially contaminated sites and health

Regarding specific sources of pollution, industrial facilities, power plants, and large boiler houses contribute significantly to ambient air pollution concentrations (European Environment Agency, 2021). Past and current industrial activities have caused air, soil, and water contamination to an extent that might threaten human health, especially in vulnerable subgroups. According to the World Health Organization definition, those areas are called "industrially contaminated sites". They are defined as: "*Areas hosting or having hosted human activities which have produced or might produce environmental contamination of soil, surface or groundwater, air, food-chain, resulting or being able to result in human health impacts*" (WHO Regional Office for Europe, 2012).

2.2.1 Oil shale, shale oil and associated health effects

Oil shale is an organic-rich sedimentary rock containing up to 50% kerogen, a solid mixture of organic chemical compounds. Massive deposits of these mineral resources are found in several countries around the globe, including Estonia, China, Israel, Jordan, Australia, Brazil and the United States. However, most are too deep and too costly to be exploited. Only China, Brazil, and Estonia produce oil shale commercially (OECD, 2017). In Estonia, oil shale has been mined, excavated, and used for electricity generation and shale oil extraction in chemical industry (Habicht, 1994). Shale oil is synthetic oil extracted from oil shale by pyrolysis. It can be refined into diesel, motor gasoline, jet fuel, and natural gas liquids. Additionally, oil shale is being processed with heat to produce chemicals, such as phenols (Speight, 2012).

According to the International Agency for Research on Cancer (IARC) 2012 monograph (IARC, 2012), crude shale oil contains larger amounts of organic nitrogen compounds and arsenic compared to crude oil. It is a viscous, waxy liquid composed of hydrocarbons (alkanes, alkenes, and aromatics) and polar components (compounds of organic nitrogen, oxygen, and sulphur). Crude shale oil is a very complex mixture, of which only a few compounds have been identified. There have been few studies of professional-specific exposure to shale oil. On the other, hand there is sufficient research on exposure to hazardous substances associated with oil shale processing, including asbestos (Kangur, 2007), diesel exhaust gases (L.E. Knudsen et al., 2005; Muzyka et al., 2003, 2004; Scheepers et al., 2002), trace elements (arsenic, cadmium, lead, mercury, nickel), hydrogen sulphide, uranium and radon, carbon monoxide, phenol, polynuclear aromatic compounds: benzo(a)pyrene and 1-nitropyrene (Anderson et al., 1997; Boffetta et al., 1997; Kivisto et al., 1997; Kuljukka et al., 1998, 1996; Scheepers et al., 2003, 2002), with aromatic compounds such as benzene and toluene (Anderson et al., 1997; Kivisto et al., 1997; Marcon et al., 1999; Scheepers et al., 2002; Sorensen et al., 2004), with sulphur dioxide and dust (Louw et al., 1986).

Carcinogenicity

Evidence of the carcinogenicity of shale oil dates back to the first half of the 20th century in Great Britain, when compelling evidence was found in cases of skin cancer, especially scrotal cancer. These cases were significant in their scale, with 65 cases of cancer of the scrotum found in workers in the Scottish shale oil industry between 1900 and 1921 (Scott, 1922a, 1922b). Exposure of cotton textile workers (mule spinners) to lubricating oil (unprotected unsanitary conditions), which at various times also contained shale oil, was strongly associated with scrotal cancer (Brockbank, 1941; Southam, 1928). Strong associations between shale oil and scrotal cancer were accepted even in a situation where epidemiological studies were lacking. From 1950–1982, a study of shale oil drilling and refining workers in Scotland had a higher mortality from skin cancer than the general population (hazard ratio 4.9 (95% CI 2.2–10.9)) (Miller et al., 1986). However, lung cancer mortality in shale oil plant workers did not differ from the general population (Miller et al., 1986; Seldén, 1987).

Over the years, animal experiments have also been carried out, where skin damage was detected in mice and rabbits when exposed to shale oil. Skin cancer, papilloma, spindle cell sarcoma, and squamous cell carcinoma occurred in study animals exposed to shale oil (Hueper, 1953; IARC, 1985; Twort and Ing, 1928; Wilson and Holland, 1988). Lung cancer also increased in mice exposed to untreated shale oil (IARC, 1985; Smith and Witschi, 1983).

Nevertheless, the studies conducted over the past thirty years have shown mixed results regarding industrial air pollution and carcinogenic impacts caused by petrochemical industries. In some cases, no associations have been found with either leukaemia or lympho-haematological and central nervous system cancers (Axelsson et al., 2010; Wilkinson et al., 1999), while in other cases, a higher incidence of Hodgkin's disease has been shown (Wilkinson et al., 1999). Regarding carcinogenicity, in some cases, higher incidences of lung, laryngeal, liver, and bladder cancers and leukaemia have been found near petrochemical industrial areas worldwide (Belli et al., 2004; Edwards et al., 2006; Petrauskaitė et al., 2002; Sans et al., 1995; Tsai et al., 2008). According to IARC, some petroleum products, such as gasoline and heavy fuel oils (including shale oil), contain toxic substances such as benzene and polycyclic aromatic hydrocarbons (PAHs) (IARC, 1985). These products have been released into the outdoor air and land in industrial regions (Harrison, 2001) and even higher exposures have occurred in workplaces (Kivisto et al., 1997; Kuljukka et al., 1996). Benzene and many of the polycyclic aromatic hydrocarbons, are classified as carcinogenic (IARC, 1983; Loomis et al., 2017).

Recently, increasing evidence has shown associations between living near industrially contaminated sites or being exposed to industrial air pollution and increased total cancer incidence and mortality (De Rocchi et al., 2021; Fernandez-Navarro et al., 2017; Lin et al., 2017; Pirastu et al., 2013b; Yuan et al., 2018). Although the primary focus has been on lung cancer (Comba et al., 2014; Lin et al., 2017; Marinaccio et al., 2011; Pirastu et al., 2013b), the increased risks have also been documented for kidney (Cong, 2018; Gensburg et al., 2009), bladder (Comba et al., 2014; Cong, 2018; Gensburg et al., 2009; Marinaccio et al., 2011), breast cancer (Garcia-Perez et al., 2016; Lewis-Michl et al., 1996; Pan et al., 2011) as well as leukaemia (Boberg et al., 2011; Bonzini et al., 2019; Cong, 2018; Garcia-Perez et al., 2010) and non-Hodgkin's lymphoma (Cong, 2018; Ramis et al., 2012; Zusman et al., 2012). Weaker evidence has been found on the prostate (Ramis et al., 2011), thyroid (Benedetti et al., 2021; Bernier et al., 2019), colorectal (López-Abente et al., 2012), liver (Comba et al., 2014), and paediatric cancer risk (Iavarone et al., 2018; Ortega-Garcia et al., 2017).

In general, IARC classified air pollution as carcinogenic to humans in 2013. Sufficient evidence has shown that exposure to outdoor air pollution and particulate matter causes lung and bladder cancer. (International Agency for Research on Cancer, 2013).

Respiratory health

Air pollution causes health risks even at relatively low levels (Dominici et al., 2022; Shi et al., 2016). World Health Organization (WHO) has indicated that air pollution is one of the leading preventable causes of disease and death globally (WHO, 2023).

Several studies have associated living near industries with increased health risks: e.g., people living close to a plant for at least 10 years had a higher risk ratio in terms of various respiratory diseases (Simonsen et al., 2010; S. P. Tsai et al., 2004). There is also robust evidence that children living near (i.e. within 5 km) industrial sites or exposed to industrial pollutants have an increased risk of adverse health outcomes compared with those living more than 20 km away or those less exposed (Alwahaibi and Zeka, 2016; Bergstra et al., 2018; Lewin et al., 2013; Nirel et al., 2014; Smargiassi et al., 2014; Wichmann et al., 2008; Wilhelm et al., 2007; C. M. Wong et al., 2016; Yang et al., 1997). It has been found that living near coal power plants had a negative impact on the development of lung function in children, even though the air in the area did not exceed local standards (Dubnov et al., 2007), which may suggest that air pollution standards are too low. However, breathing difficulties, chronic asthma, and asthma-related deaths have not increased among women living near the industry (Pignato et al., 2004; Tsai et al., 2003). A risk group is also oil shale miners, among whom an increased risk of pulmonary fibrosis and airway obstruction has been shown (Louw et al., 1986).

Reproductive health
Ambient air pollution in industrial areas also has prenatal effects. Adverse birth outcomes such as low birth weight and preterm birth are more present in the vicinity of industrial areas rather than in green neighbourhoods (Casey et al., 2018; DeCicca and Malak, 2020; Ha et al., 2015; Lin et al., 2004; Mohorovic, 2004; Nielsen et al., 2019; S.-S. Tsai et al., 2004; Yang et al., 2017; Yang and Chou, 2018) that can be the consequence of industrial contamination. For both foetal chromosome damage and preterm birth, the risk has been higher for women aged 35 years or older who had been living in industrially polluted areas for an extended period (Brender et al., 2008; Dahal et al., 2022).

2.2.2 Oil-shale industry-related contaminated sites in Estonia

Industrial activity in Ida-Viru County, in North-East Estonia, consists mainly of oil shale extraction, power generation and shale oil production (OECD, 2017). Those industrially contaminating productions emit large amounts of particulate matter (PM_{10}), sulphur dioxide (SO_2), and nitrogen oxides (NO_x), as well as several other industrial pollutants like phenols and benzene released in oil extraction and other trace elements in Estonia (OECD, 2017). Moreover, workers in the mines and in the chemical industries have been exposed to health hazards due to the exposure to diesel exhaust in mines and the toxicity of shale oil and its derivates (Office of Technology Assessment, 1980). Environmental pollution (atmosphere, soil, groundwater) in the area was especially alarming during the 1980s and 1990s due to unprotected hazardous landfills containing ash from oil shale combustion and semi-coke and retorting waste from refining (Raukas and Punning, 2009).

The usage of oil shale was most significant during the 1980s (up to 30 million tonnes per year); after the collapse of the Soviet Union, it decreased gradually until 1999 and has been 10 and 15 million tonnes per year during the last 25 years (Statistics Estonia, 2016). During the past decade, the pattern of oil shale usage has transformed, resulting in a significant reduction in air pollution emissions. Shale oil factory Enefit 280 commenced operation near Narva in 2012, and two Petroter factories at Kohtla-Järve (2014/2015) and the 300 MW Auvere Power Plant (2015) were opened (TalTech Virumaa kolledži põlevkivi kompetentsikeskus, 2016). However, despite the measures taken to reduce the emission of air pollutants, the health status of residents in the oil shale industry region is still worse in many aspects than elsewhere in Estonia. Life expectancy at birth among females is two years less and among males three years less than the Estonian average (Statistics Estonia, 2022a). the percentage of adults who have a long-term illness is 10% higher in Ida-Viru County (57%) than on average in Estonia (47%). Healthy life years among females is five years; among males, three years less than the Estonian average (Statistics Estonia, 2022c).

2.2.3 Health effect studies in the oil-shale region

Health effects related to the oil shale sector were extensively analysed in Estonia up to the early 1990s when the environmental conditions and health indicators of the inhabitants and their interrelations, were thoroughly studied (Этлин, 1989). After that, for two decades, mainly occupational health risks such as exposure to exhaust gases during mining and polycyclic aromatic hydrocarbons and benzene in the shale oil industry were studied (Anderson et al., 1999; Kivisto et al., 1997; Kuljukka et al., 1996; Marcon et al., 1999; Muzyka et al., 2004; Sorensen et al., 2004). Even though the Estonian oil shale industry is relatively unique, refining shale oil is considered to have health effects similar to other refining operations (Office of Technology Assessment, 1980). Thus, studies of the people living in the vicinity of refineries continue to be of high relevance.

Maasikmets et al. (Maasikmets et al., 2013) have indicated that in Estonia, industrial emissions play a central role only in North-East Estonia in Ida-Viru County. Locally generated pollution is coupled with air pollution from other regions and countries (Laan et al., 2014). Even the highest particulate pollution concentrations over time have been recorded in Tallinn and Tartu, PM_{10} concentrations have also been high in Kohtla-Järve and Narva. According to a recent health impact assessment, air pollution in Ida-Viru County (of which 20% is based on industry) caused around 140 premature deaths, that results in 1,620 years of life lost and life expectancy to be decreased by 0.75 years in 2020 (Orru et al., 2022). Epidemiological studies in Estonia have shown an association between levels of particulate matter from traffic and the occurrence of cardiac diseases (Orru et al., 2009), residential heating and respiratory diseases (Pindus et al., 2016) and an elevated risk of developing cardiac disease among those living near high-traffic streets and roads (Pindus et al., 2016). Also, during air pollution episodes with poor air quality, the increase in short-term mortality has been reposted in association with fine particles and near-surface ozone (Läll et al., 2013; Olstrup et al., 2022).

Earlier studies in an industrial area of Ida-Viru County have indicated that the activities of the oil shale sector may affect the respiratory health of the residents (Tefanova et al., 1993; Vasar et al., 2011; Этлин, 1989). According to surveys conducted during 1971–1981, children living in the Ida-Viru area had significantly smaller lung capacity and higher morbidity than children living in the reference areas (also in Estonia). The studies of Etlin (1989) showed that the overall number of doctor's appointments was 1.3 times higher in Ida-Viru County than in other regions of Estonia, and the frequency of abnormal birth weight was also 60% higher (Этлин, 1989). The birth weight of newborns in Ida-Viru County was 4.8% lower than on average in Estonia from 2004–2018 (Dahal et al., 2022). There were also 1.6 times higher odds of having a preterm (<37 weeks) child living less than 3 km from the industrially contaminated sites.

During the 1990s, several complex surveys were conducted among preschool children living in two cities in North-East Estonia (Kohtla-Järve and Jõhvi), examining the clinical and immunological parameters of their health condition, and the impact of air pollution on the level and structure of their morbidity. The results indicated that children aged 3 to 6 years living in Kohtla-Järve had a higher overall risk of morbidity and a higher morbidity risk for respiratory diseases (Tefanova et al., 1993). Children living in Narva (a city in North-East Estonia) have also been found to have more often respiratory and asthma-like symptoms than those living in Tallinn, Pärnu, or Elva (Bjorksten et al., 1998; Julge et al., 2006). According to Vasar *et al.* (Vasar et al., 2011), in the early 2000s, asthma was more often diagnosed, and respiratory symptoms indicative of asthma in Ida-Viru County than in other parts of Estonia.

Regarding cancer, higher lung and stomach cancer rates were recorded in the industrial areas in North-East Estonia in the 1970s (Purde and Rahu, 1979). Later, during the 1980s, Etlin et al. (Этлин, 1989) conducted several epidemiological studies in the industrial area in Ida-Viru County to investigate cancer sites such as lung, stomach, and skin cancer. However, none of the cancer sites showed significantly ($p > 0.05$) higher incidence in the industrial area compared to the Estonian average. In the past, incidence rates for all cancers combined and specifically lung cancer, have been a little higher in North-East Estonia (Ida-Viru County and the towns of Narva and Kohtla-Järve) for males when compared with the rest of Estonia (Thomson et al., 1996). In the earlier decade, the deaths due to malignant neoplasms in North-East Estonia have been higher than on average in Estonia (National Institute for Health Development, 2012).

Two drinking water quality assessments have been conducted in Ida-Viru County in recent years (Lukk et al., 2020; Tamm et al., 2015). In larger cities and areas related to the oil shale sector (Narva, Sillamäe, Kohtla-Järve, Jõhvi, Kiviõli etc.), mainly public water supply was used. However, in rural settlements, the population's share of public water users was much smaller, around 4% of the inhabitants in Ida-Viru County receive water from private water supply systems. These boreholes and wells are not monitored and therefore, there were no data on the water quality of these waterworks (Tamm et al., 2015).

Since most of the population uses public water supplies that are constantly monitored, the excessive risk to the public health via water is relatively small. Based on earlier studies (Lukk et al., 2020; Tamm et al., 2015), the effect of different air pollutants on health symptoms in cities is apparent; however, information on the health effects of air pollution in the industrial areas of North-East Estonia is limited.

2.3 Rationale of the studies

The rationale for these studies is rooted in the significant environmental and public health concerns associated with oil shale-related industrial pollution in Ida-Viru County, Estonia. The literature review has highlighted various adverse health effects linked to industrial contaminants, including respiratory diseases, cardiovascular conditions, and increased cancer incidence. Despite previous research efforts, gaps remain in understanding the long-term health effects of exposure to industry-specific pollutants, such as industry-based fine particles, benzene, phenol, formaldehyde, and non-methane hydrocarbons. This research aims to address these gaps and provide a more comprehensive analysis of the health impact on populations living in industrially contaminated areas.

One of the primary motivations for this study is the observed health disparities in Ida-Viru County compared to the rest of Estonia. The region has lower life expectancy, higher mortality rates from cardiovascular diseases, and increased cancer morbidity, particularly lung cancer. Previous epidemiological studies have suggested links between industrial emissions and these health issues. Yet the evidence remains inconclusive due to methodological limitations, lack of updated exposure assessments, and insufficiently representative sample populations. These studies will adopt a more systematic and robust approach to examining the associations between environmental exposure and health outcomes.

Additionally, the perception of air pollution and its impact on well-being is an underexplored area that this research seeks to address. Residents of Ida-Viru County report higher levels of environmental annoyance and concerns about air quality, which may contribute to mental and physical health issues. These studies will provide insights into the psychosocial burden of living in an industrially contaminated region by investigating the relationships between perceived pollution, actual air quality data, and health indicators.

Furthermore, a critical gap in the literature pertains to the changing landscape of industrial emissions and its implications for public health. Over the past decades, emissions from the oil shale industry have fluctuated due to policy changes, economic shifts, and technological advancements. However, whether these changes have translated into improved health outcomes for local populations remains unclear. This research will analyse time trends in air pollution, respiratory health concerns, and cancer incidence rates to determine the long-term effects of industrial activity and regulatory interventions.

Methodological advancements in environmental epidemiology and exposure assessment also provide an opportunity to refine the study design. By utilizing geospatial analysis, air quality monitoring data, and health records, these studies aim to produce more accurate assessments of exposure-response relationships. Additionally, by incorporating population-based surveys, this research will evaluate public attitudes toward environmental quality and its potential impact on health and well-being.

In summary, the following studies are designed to bridge existing knowledge gaps regarding the health effects of industrial pollution in Estonia's oil shale region. By addressing theoretical ambiguities, improving methodological rigour, and incorporating community perspectives, this research will contribute to evidence-based policy recommendations aimed at mitigating the adverse health impacts of industrial activities and promoting sustainable environmental management.

3. AIMS OF THE RESEARCH

The overall aim of the thesis was to assess the health effects of people living in oil shale industry region. The specific objectives were:

1. to identify the air quality situation in Ida-Viru County and people's annoyance regarding air pollution;
2. to study the relationships between industrial pollutants and the health status of adult residents;
3. to detect whether the prevalence of respiratory problems among children living in oil shale industry region remain higher than elsewhere in Estonia and is associated with pollution from oil shale industries;
4. to analyse the time trends in cancer incidence rates in the oil shale industry-affected areas in Estonia and compare those with national incidence rates over time.

4. MATERIALS AND METHODS

The studies presented in this thesis are part of the series of epidemiological investigations, “Studies of the health impact of oil shale sector – SOHOS”. The current thesis uses data from the SOHOS cross-sectional study of the people living in three different counties (approved by the Research Ethics Committee of the University of Tartu (231/T-10)). In comparison, the SINPHONIE (Schools Indoor Pollution and Health: Observatory Network in Europe) study (Csobod et al., 2014) data are also used as part of the research. SINPHONIE was a multidisciplinary research project covering the areas of health, environment, transport, and climate change aimed at improving air quality in schools and kindergartens. Twenty-four countries across Europe participated in the SINPHONIE project, and the data collection in Tartu County (currently used as a reference area) took place from January–February 2012.

4.1 Study areas

The oil shale industrial area is situated in Ida-Viru County in North-East Estonia, surrounded from the East by Russia, from the north by the Gulf of Finland, from the south by Lake Peipsi and from the west by Lääne-Viru County (Figure 1). Approximately 145,000 people were living in Ida-Viru County in 2015. The sources of air and other environmental pollution in the region have been quite complex – different industrial activities as well as pollution from traffic, local heating, etc.

Lääne-Viru County is situated west of Ida-Viru County and has a smaller population (60,000 inhabitants in 2015) (Figure 1). Tartu County situates in South-East Estonia, with a population of around 150,000 inhabitants in 2015. Lääne-Viru and Tartu Counties are non-industrially polluted regions and were included as reference areas.

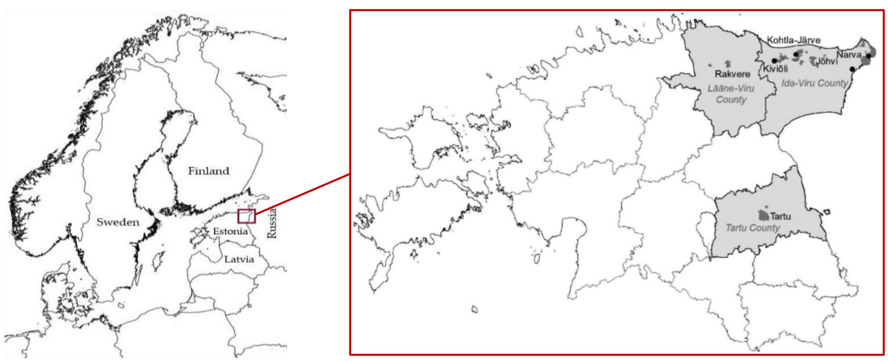

Figure 1. Map of Northern Europe showing the location of Estonia (left). Map of Estonia (right) with counties studied (shaded areas), locations of the study populations (dark grey areas), and the location of oil shale industry facilities and power plants (black dots). The maps were made with QGIS 2.18 software. The administrative boundaries were provided by EuroGeographics and the Estonian Land Board (Estonian Land Board, 2019; EuroGeographics, 2020).

4.2 Air quality monitoring and pollution dispersion modelling

The annual mean concentrations of phenol, benzene, formaldehyde, non-methane hydrocarbons, particulate matter (PM_{10}) and fine particles ($PM_{2.5}$) in 2013 were modelled in 1×1 km grids in Ida-Viru County using an Eulerian air quality dispersion model that is part of the Airviro Air Quality Management System (SMHI, Sweden; http://airviro.smhi.se) (Airviro, 2010). Airviro is a widely used web-based air pollution data management tool that uses data on air emissions, measured levels of air pollution, and measured meteorological variables (Orru et al., 2011). The industrial pollutant emissions were retrieved from the ambient air emission database OSIS2013, which consists of annual emissions (tons per year) reported by companies and confirmed by the Estonian Environmental Board. Transport-sector emissions came from the database Traffic2007, and domestic heating emissions from the local heating database. The modelled concentrations were validated with monitored levels from monitoring stations in Ida-Viru County. Regular monitoring takes place in Ida-Viru County in Kohtla-Järve city, Narva city and Sillamäe port. The shale oil extraction factories are situated in Kohtla-Järve, Kiviõli, and near Narva. For the visualization, the model output was generalized and classified into five classes using ArcGIS scripting environment ArcPy. The obtained annual concentrations of modelled pollutants per grid cell were linked with the geo-code of each respondent's home address in ArcGIS.

4.3 Study questionnaires

4.3.1 Children's study

The study population consisted of 1,326 randomly selected 3rd and 4th grade schoolchildren and their parents from twenty-five schools, aged between 8 and 12 years and living in North-East Estonia (in Ida-Viru and Lääne-Viru Counties) or South-East Estonia (Tartu County). Most (98%) of the children were 9–10 years old. There were slightly more girls (52%) than boys (48%). There were no significant differences in the sociodemographic characteristics of subjects from different regions.

Questionnaires on health and socio-demographics were distributed to children by teachers and were completed by parents and children together. The questionnaire focussed on respiratory health and included questions on physician-diagnosed asthma, the frequency of asthma attacks, allergies etc. The following questions were included in the current thesis analysis:

1. "Has your child ever had wheezing or whistling in the chest at any time in the past?" Yes/No
2. "Has your child ever had a problem with sneezing, runny nose, or a blocked nose when he/she did not have a cold or flu?" Yes/No
3. "Has your child ever had asthma diagnosed by a physician?" Yes/No

4. “Has your child ever had attacks of asthma?” Yes/No
5. “Has your child had wheezing or whistling in the chest without cold in the past 12 months?” Yes/No
6. “In the past 12 months, has your child had a dry cough at night, apart from a cough associated with a cold or chest infection?” Yes/No
7. “Does your child have a dry cough without a cold on some days during the year?” Yes/No
8. “Does your child have phlegm without a cold on some days during the year?” Yes/No

4.3.2 Adults’ study

A postal SOHOS questionnaire was sent in 2014 and 2015 to 2,097 residents aged 18–70 years living in Ida-Viru County. In addition, questionnaires were sent to a reference group of 403 individuals aged 18–70 years living in neighbouring Lääne-Viru (west) County and to 2,750 individuals aged 18–40 years living in Tartu County. All participants were randomly selected by the Estonian Population Registry according to the age and ethnic structure of the area. In addition, the information collected during a similar earlier survey entitled “Respiratory Health in Northern Europe – RHINE III”, carried out in 2011 and 2012 in Tartu (Johannessen et al., 2014), was included in the Tartu reference group. RHINE III sample consisted of 2,231 participants from Tartu aged 40–65 years old, of whom 1,370 responded to the questionnaire.

All participants received a postal questionnaire about their socio-economic situation, general health, respiratory symptoms, chronic diseases, indoor and outdoor environment, working history, and health behaviour (Appendix A of Paper II). The SOHOS questionnaire was largely based on the RHINE III questionnaire, but additional questions were added according to the needs of the SOHOS study. According to their self-defined ethnicity in the population registry, the questionnaire was sent in Estonian or Russian.

4.4 Clinical examinations

Schoolchildren who responded to the survey were invited to a clinical examination, during which the content of fractional exhaled nitric oxide (FeNO) was determined, with NIOX MINO®. Values of fractional exhaled nitric oxide differ individually, but for children, 20–35 ppb (parts per billion) is considered intermediate levels of FeNO (Dweik et al., 2011; Wang et al., 2017). In the current study, based on earlier studies as well as the clinical expertise of Estonian paediatric allergists, FeNO values of ≥ 30 ppb in children were defined as ‘high’.

4.5 Registry-based analyses

Population-based data on cancer cases were retrieved from the Estonian Cancer Register for the years 1992–2015. Estonia has had a population-based cancer register since 1968. Reporting of cancer cases to the Cancer Register is mandatory for all physicians and pathologists in Estonia who diagnose and treat neoplasms. The data quality of the register has been monitored for many years, and it meets all international quality standards (Põder, 2015).

When obtaining information about different neoplasms from the register, WHO ICD-10 codes were used (WHO, 2016), we included cancer sites in the study that have previously been indicated as having association with different industrial activities: lung cancer (C34), kidney cancer (C64), bladder cancer (C67), breast cancer (C50), leukaemia (C91–C95), and non-Hodgkin's lymphoma (C82–C85) (Attfield et al., 2012; Belli et al., 2004; Edwards et al., 2006; Miller et al., 1986). Patient information (gender, date of birth, nationality, place of residency on municipality level) and tumour characteristics (date of diagnosis) were extracted.

4.6 Exposure assessment

Study participants were linked to modelled air pollution concentrations (e.g. PM_{10}, $PM_{2.5}$, benzene, phenol, and formaldehyde) based on their home addresses (paper I). For this, their home addresses were geocoded which converts addresses into geographic coordinates that enable the linking of residences with the environment. Additionally, the distance from each participant's home to the nearest industrial site was calculated to assess proximity-related exposure (Figure 2).

For the purpose of ecological analysis (paper II), living in the three cities of Kohtla-Järve (Järve district), Kiviõli and Püssi (termed the 'Chemical industry region') and responding to the questionnaire were considered to be highly exposed to industrial pollutants. Respondents from the 'Chemical industry region' and from the city of Narva, which has two electricity generation plants using fuel extracted from oil shale located nearby (termed the 'Chemical industry and power plant region'), were considered to be highly exposed to industrial pollutants as well–all the named places where within the radius up to 5 km (Figure 2).

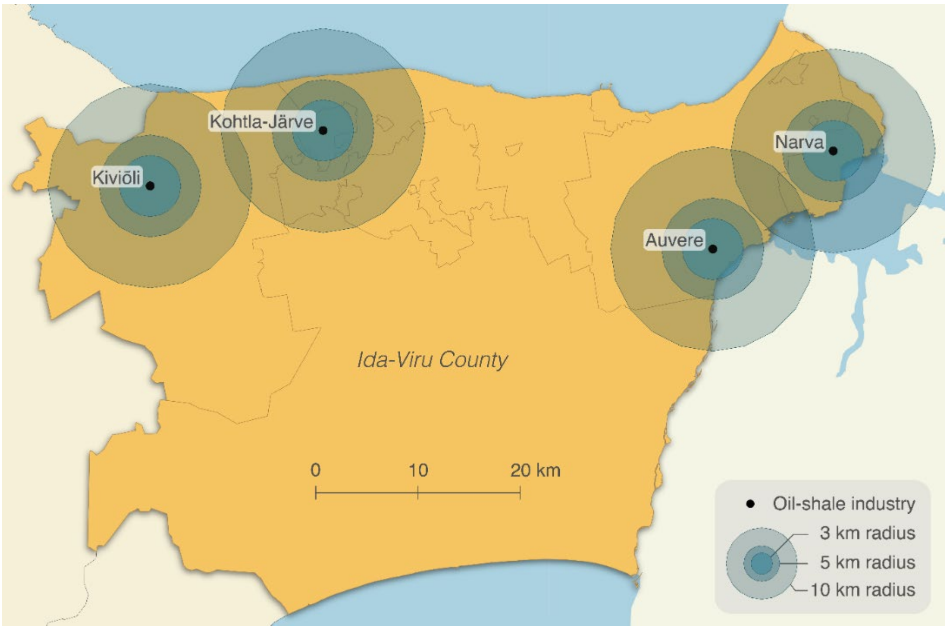

Figure 2. Oil shale industries in Ida-Viru County and 3 km, 5 km, and 10 km buffers around them. Basemap: © Land Board.

For cancer-related ecological analysis (Paper III), all respondents living in the three cities of Kohtla-Järve (Järve district), Kiviõli and Püssi (termed the 'Chemical industry region') were considered to be exposed to higher levels of industrial pollutants. Respondents from the 'Chemical industry region' and from the city of Narva, which has two electricity generation plants using fuel extracted from oil shale located nearby (termed the 'Chemical industry and power plant region'), were considered to be exposed to higher levels of industrial pollutants as well.

In the cancer incidence study, the municipalities in Ida-Viru County were divided into those with a greater degree of exposure to industrial pollution (termed the "oil shale areas") and less exposure to industrial pollution (termed the "non-oil shale areas") based on Geological Survey of Estonia data on the mines, the locations of industrial sites, and Population Register data on people's places of residence at the time of cancer diagnosis (Figure 3). The majority of the people living in the area are immigrants or their descendants, who moved there from all over the Soviet Union during the 1960s and the 1970s, making it a predominantly Russian-speaking region. Many still speak only Russian, making it a significant barrier to living and working elsewhere in Estonia (Statistics Estonia, 2001; Tiit and Servinski, 2013). Therefore, exposure assessment based on the permanent residential location of the people was considered appropriate. "Oil shale areas" are the municipalities with industrial activity in shale oil chemistry and oil shale mining.

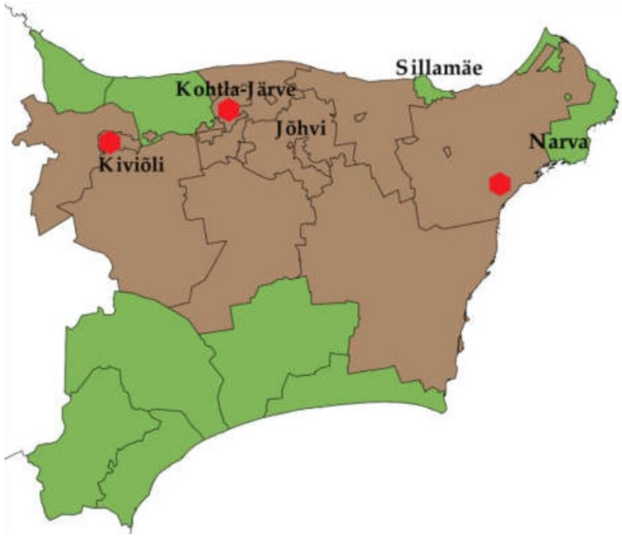

Figure 3. Map of Ida-Viru County, Estonia, showing different municipalities (right). Municipalities under observation: oil-shale production and mining areas – brown, non-oil shale areas – green. The locations of shale oil extraction facilities are shown as red dots. The maps were made with QGIS 2.18 software. The administrative boundaries were provided by EuroGeographics and Estonian Land Board (Estonian Land Board, 2019; EuroGeographics, 2020)

4.7 Statistical analyses

Statistical analyses were performed using the statistical program Stata/SE (version 12.1 and 14.2 (StataCorp, College Station, TX, USA) (Papers I–III).

According to the home address (Paper I–II), the respondents were divided into three groups: residents of Ida-Viru County, Lääne-Viru County, or Tartu County. Subsequently, respondents' prevalence of respiratory symptoms and chronic diseases, as well as their risk perception and socio-economic indicators, were calculated. The differences between the groups and counties were tested with a chi-square test. Furthermore, the differences between genders, ethnicities, and employed/unemployed in the oil shale sector were tested.

The relationships between self-reported health effects and modelled pollutant concentrations at the respondents' home addresses in 1x1 km grids were studied using logistic regression analysis. The regression models were adjusted for possible confounders such as gender, age, body mass index (BMI), environmental tobacco smoke (ETS), smoking history, and income per family member. Additionally, for schoolchildren, it is also for parents' highest education and BMI by WHO BMI-for-age (5–19 years) (WHO, 2007).

Annual age-standardised cancer incidence rates for 1992–2015 were calculated per 100,000 person-years using the population size in the administrative divisions as obtained from the Population Register of Estonia. Observed cancer sites in males and females are reported for all ages and in the age groups 0–19, 20–29, 30–39, 40–49, 50–59, 60–69, 70–79, ≥80 years. Subsequently, due to the small number of cases, we calculated three-year moving average incidence rates to reduce the fluctuating effect of different single years in the trend analysis.

Based on age-standardized morbidity rates (1992–2015), trend figures and linear trendlines were drawn for all observed cancer sites using Microsoft Excel (Office 365, Microsoft Corp, WA, USA). The paired t-test was used to compare the cancer incidence rate in the different areas (separately among males and females). A p-value of < 0.05 was considered statistically significant.

5. RESULTS

5.1 Air quality in Ida-Viru County (Paper I, II)

Based on modelled annual average air pollution concentrations in Ida-Viru County, the highest levels of $PM_{2.5}$ and PM_{10} appear in the Kohtla-Järve region, the highest levels of benzene in the Narva region, with a slight increase also in Kohtla-Järve region, and the highest levels of phenol in the Narva region, with a slight increase also in the Kiviõli area. The highest levels of formaldehyde and hydrocarbons (NMHC) appear in Kohtla-Järve and Kiviõli region (Figure 4).

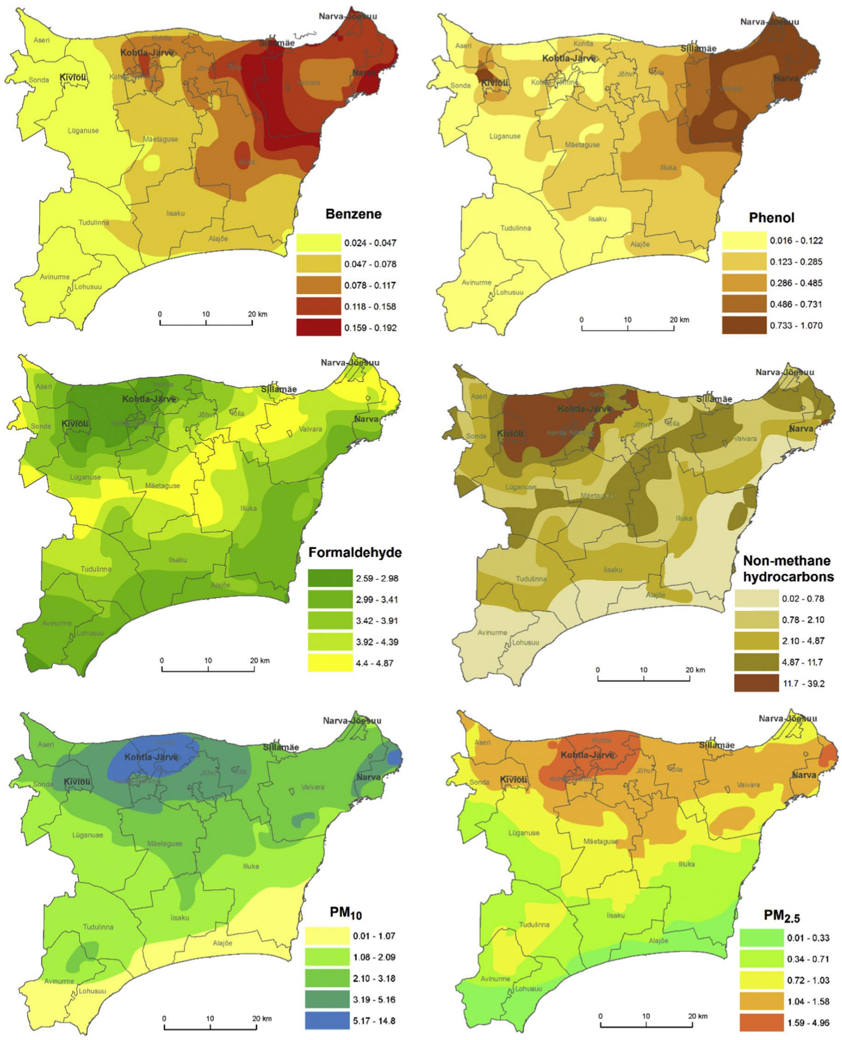

Figure 4. Oil shale industry facilities, air quality monitoring station locations and annual (2013) average concentrations (µg/m^3) of benzene, phenol, formaldehyde, NMHC, coarse particles (PM_{10}), and fine particles ($PM_{2.5}$) in the ambient air of Ida-Viru County.

5.2 Prevalence of respiratory symptoms, asthma and high FeNO levels among schoolchildren (Paper II)

The study of the respiratory health among third and fourth-grade students showed that the prevalence of the various respiratory symptoms was highest in Ida-Viru County. Symptoms such as ever having had wheezing, rhinitis without a cold, nocturnal dry cough without a cold during the past year, dry cough without a cold and phlegm were statistically significantly more prevalent in Ida-Viru County than in Tartu County (Table 1).

Table 1. Prevalence (%) of respiratory symptoms, asthma and high FeNO levels in the different counties of Estonia

	Ida-Viru County	Lääne-Viru County	Tartu County
Based on questionnaire			
Ever had			
Wheezing	21.5[1]	23.3	10.3
Rhinitis without cold	35.3[1,2]	24.6	13.8
Asthma diagnosis by physician	12.8	10.1	7.2
Asthma attack	10.8	6.6	N/A
During last 12 months			
Wheezing without cold	20.0	20.0	N/A
Nocturnal dry cough without cold	23.7[1,2]	16.0	5.9
Some days during a year			
Dry cough without cold	16.9[1,2]	7.8	5.0
Phlegm	9.5	6.1	2.0
Clinical examination			
FeNO ≥ 30 ppb	15.0[1,2]	8.3	4.2
FeNO ≥ 30 ppb and no asthma diagnosis	11.2[1,2]	4.2	4.9

N/A not included in the questionnaire for Tartu County.
[1] Statistically significant difference ($p < 0.05$) in prevalence between Ida-Viru County and Tartu County.
[2] Statistically significant difference ($p < 0.05$) in prevalence between Ida-Viru County and Lääne-Viru County.

The prevalence of physician-diagnosed asthma was: 12.8% in Ida-Viru County and 10.1% in Lääne-Viru County and 7.2% in Tartu County, that was significantly lower ($p < 0.05$) than in Ida-Viru County. Approximately 11% of the children in Ida-Viru County reported experiencing attacks of asthma, whereas in Lääne-Viru County, the prevalence was 6.6%.

The prevalence of high fractional exhaled NO (FeNO) (values ≥ 30 ppb) among studied students was more than three times higher in Ida-Viru County (15.0%) than in Tartu County (4.2%), and two times higher than in Lääne-Viru County (8.3%) and the differences were also statistically significant. Moreover, 11.2% of children in Ida-Viru County had high values of FeNO but no previous asthma diagnosis by a physician. This was significantly higher in Ida-Viru County than in Lääne-Viru County (4.2%).

5.3 Prevalence of respiratory symptoms and chronic health effects among adults (Paper I)

This research showed that the residents of Ida-Viru County complained statistically significantly more frequently ($p < 0.05$) about wheezing, chest tightness, shortness of breath, asthma attack, long-term cough, hypertension, heart disease, myocardial infarction, stroke, diabetes compared to residents of Tartu and to residents from neighbouring Lääne-Viru County when it came to wheezing (Table 2). Men living in Ida-Viru County suffered statistically significantly more frequently ($p < 0.05$) from chronic obstructive pulmonary disease, wheezing, and heart attacks than women and men in reference areas (data not shown) (Orru et al., 2015). There were statistically significant differences between ethnic groups, with non-Estonians suffering more from most of the health complaints and chronic diseases (Table 2).

Table 2. The prevalence of respiratory and cardiovascular diseases in different counties and among ethnic groups, n (%).

	Ida-Viru County	**Lääne-Viru County**	**Tartu County**	**Estonians**	**Non-Estonians**
Ever had					
Wheezing	**358 (42.2 [1])**	66 (36.2)	427 (17.9)	405 (30.0)	**353 (46.0 [3])**
Chest tightness	**256 (30.1 [1])**	42 (23.3)	403 (16.9)	215 (15.9)	**242 (31.6 [3])**
Shortness of breath	**165 (19.4 [1])**	27 (14.6)	286 (12.0)	143 (10.6)	**156 (20.4 [3])**
Attack of coughing	**384 (45.2)**	77 (42.2)	997 (41.8)	539 (39.9)	324 (42.3)
Asthma attack	**65 (7.6 [1])**	12 (6.7)	91 (3.8)	62 (4.6)	**60 (7.8 [3])**
During last 12 months					
Wheezing without a cold	**275 (32.4 [1,2])**	37 (20.5)	539 (22.6)	251 (18.6)	**254 (33.1 [3])**
Long-term cough	**249 (29.3 [1])**	41 (22.3)	498 (20.9)	259 (19.2)	**242 (31.6 [3])**
Nose allergies/hay fever	185 (21.8)	41 (22.5)	577 (24.2)	320 (23.7)	157 (20.5)
Asthma	64 (7.5)	15 (8.0)	174 (7.3)	91 (6.7)	58 (7.5)
COPD	20 (2.4)	3 (1.7)	24 (1.0)	12 (0.9)	**21 (2.7 [3])**
Hypertension	**292 (34.4 [1])**	59 (32.2)	370 (15.5)	181 (13.4)	**250 (32.6 [3])**
Heart disease	**138 (16.3 [1,2])**	18 (10.0)	241 (10.1)	85 (6.3)	**130 (16.9 [3])**
Myocardial infarction	**66 (7.8 [1])**	7 (4.1)	48 (2.0)	16 (1.2)	**61 (7.9 [3])**
Stroke	**31 (3.6 [1])**	4 (2.4)	24 (1.0)	11 (0.8)	**31 (4.1 [3])**
Diabetes	**84 (9.9 [1])**	11 (5.8)	69 (2.9)	35 (2.6)	**72 (9.4 [3])**

[1] Respondents from Ida-Viru County different ($p < 0.05$) from respondents from Tartu.
[2] Respondents from Ida-Viru County different ($p < 0.05$) from respondents from Lääne-Viru County.
[3] Non-Estonian respondents different ($p < 0.05$) from Estonian respondents; Values in bold: $p < 0.05$.

Residents who were working or had been working in the oil shale sector (n = 241), compared to those not been working (n = 540), had significantly more frequently ($p < 0.05$) experienced wheezing (32.8% vs 30.0%), chest tightness (33.3% vs 27.4%), hypertension (37.3% vs 29.8%), heart disease (17.4% vs 12.6%), myocardial infarction (8.7% vs 5.9%), stroke (5.0% vs 2.2%), and diabetes (10.4% vs 8.3%).

5.4 Association of respiratory symptoms in schoolchildren living in an oil shale industry area (Paper II)

There were no statistically significant differences in the sociodemographic characteristics of children living within a 5 km radius of a shale oil industry site 'Chemical industry region' or a power plant 'Chemical industry and power plant region', compared to subjects living in the rest of Ida-Viru County (Paper II). The overall prevalence of the different respiratory symptoms was lower in each of the oil shale industry reference regions (Lääne-Viru and Tartu County) compared to Ida-Viru County. The combined level of high FeNO values was highest for the 'Chemical industry region' and 'Chemical industry and power plant region', together with 15.9%, compared to the rest of Ida-Viru County. The prevalence of high FeNO values (≥ 30 ppb) was 0.9% higher in the 'Chemical industry region' (12.1%) and 0.6% higher in the 'Chemical industry and power plant region' (11.8%) than in Ida-Viru County overall (Paper II).

In the statistical analysis, the crude unadjusted model for schoolchildren living in the 'Chemical industry and power plant region' showed a 1.57 (95% CI 1.22–2.02) higher odds ratio of having rhinitis without a cold; a 1.46 (95% CI 1.22–2.02) higher odds ratio of having high exhaled nitric oxide values; and a 1.57 (95% CI 1.02–2.41) higher odds ratio of having high levels of FeNO without an asthma diagnosis compared to children living outside of 5 km radius. The adjusted model for subjects living in the 'Chemical industry region' and/or 'Chemical industry and power plant region' showed a 1.63 (95% CI 1.03–2.60) higher odds ratio of having high levels of FeNO without an asthma diagnosis (Table 3) compared to children living in reference areas.

Table 3. Relationships between respiratory symptoms, asthma and high FeNO levels for subjects living in a 'Chemical industry region' or in a 'Chemical industry and power plant region' (odds ratios (OR), 95% CI).

	Model 1		Model 2	
	Chemical industry region	Chemical industry and power plant region	Chemical industry region	Chemical industry and power plant region
Based on questionnaire				
Ever had				
Wheezing	0.91 (0.64–1.29)	1.14 (0.84–1.53)	0.78 (0.53–1.15)	0.88 (0.62–1.22)
Rhinitis without cold	1.40 (0.05–1.87)	**1.57 (1.22–2.02)**	1.18 (0.85–1.62)	1.25 (0.93–1.67)
Asthma diagnosis by physician	0.89 (0.58–1.38)	0.87 (0.60–1.26)	0.79 (0.49–1.27)	0.71 (0.46–1.07)
Asthma attack	0.92 (0.57–1.49)	0.89 (0.58–1.36)	0.83 (0.49–1.40)	0.75 (0.47–1.18)
During last 12 months				
Wheezing without cold	0.62 (0.31–1.24)	0.74 (0.41–1.34)	0.57 (0.27–1.21)	0.68 (0.35–1.32)
Nocturnal dry cough without cold	1.21 (0.87–1.70)	**1.38 (1.03–1.84)**	1.02 (0.71–1.47)	1.01 (0.73–1.41)
Some days during a year				
Dry cough without cold	1.32 (0.76–1.70)	1.36 (0.96–1.92)	1.04 (0.68–1.60)	1.09 (0.74–1.62)
Phlegm	0.81 (0.05–2.13)	1.52 (0.99–2.35)	1.17 (0.70–1.94)	1.19 (0.75–1.91)
Clinical examination				
FeNO ≥ 30 ppb	1.33 (0.90–1.97)	**1.46 (1.01–2.09)**	1.29 (0.84–1.97)	1.44 (0.97–2.15)
FeNO ≥ 30 ppb and no asthma diagnosis	1.43 (0.91–2.24)	**1.57 (1.02–2.41)**	1.43 (0.89–2.31)	**1.63 (1.03–2.60)**

Model 1 – unadjusted model.
Model 2 – adjusted for sex, age, BMI, parents' education, and family income.
The odds ratios in bold are statistically significant ($p < 0.05$).

5.5 Association between air pollution exposure and respiratory health and related diseases (Paper I, II)

5.5.1 Effects on children

Children exposed to higher levels of industry-specific air pollutants, such as benzene (Figure 4), were found to have significantly ($p < 0.05$) higher odds of most of the analysed respiratory symptoms. These included rhinitis without a cold, attacks of asthma, dry cough during the night over the last 12 months, dry cough without a cold and phlegm some days during the year. Additionally, these children showed increased prevalence of higher values of FeNO (≥ 30 ppb).

Schoolchildren living in the areas with the highest levels of formaldehyde had higher odds ratios of most respiratory symptoms, including physician-diagnosed asthma. These subjects also showed the highest odds ratios (1.22, 95% CI 1.06–1.41) of high FeNO levels; these were higher again (1.26, 95% CI 1.06–1.50) among those subjects without a concurrent asthma diagnosis. Children living in the areas with the highest levels of phenol and non–methane hydrocarbons (NMHC) had 1.01 (95% CI 1.00–1.01) and 1.75 (95% CI 1.75–2.62) higher odds ratios of high FeNO levels, respectively (Table 4). Lower levels of fine particles ($PM_{2.5}$) were associated with higher FeNO levels, both with and without an asthma diagnosis.

Table 4. Association (odds ratios and 95% confidence intervals) between respiratory symptoms and oil shale industry-associated pollutants

	Benzene	**Phenol**	**Form-aldehyde**	**NMHC**	**PM_{10}**	**$PM_{2.5}$**
OR* (95% CI), per 1 μg/m³ increase in exposure (benzene and phenol per 1 ng/m³)						
Questionnaire						
Ever had						
Wheezing	1.01 (0.98–1.04)	1.00 (0.99–1.01)	1.01 (0.90–1.13)	0.95 (0.92–0.99)	1.00 (0.95–1.06)	1.04 (0.95–1.14)
Rhinitis without cold	**1.03 (1.01–1.06)**	1.00 (0.99–1.01)	**1.13 (1.02–1.25)**	1.01 (0.98–1.03)	1.00 (0.95–1.05)	0.93 (0.86–1.01)
Asthma diagnosis by physician	1.04 (0.99–1.08)	1.00 (0.99–1.01)	**1.17 (1.00–1.36)**	0.96 (0.92–1.01)	0.98 (0.91–1.05)	0.94 (0.83–1.06)
Asthma attack	**1.05 (1.01–1.10)**	1.00 (0.99–1.00)	**1.21 (1.04–1.42)**	0.97 (0.92–1.01)	0.98 (0.92–1.05)	0.91 (0.81–1.03)
During last 12 months						
Wheezing without cold	1.04 (0.98–1.10)	1.00 (0.99–1.01)	1.18 (0.94–1.49)	0.96 (0.90–1.03)	0.96 (0.86–1.07)	0.93 (0.77–1.12)
Nocturnal dry cough without cold	**1.04 (1.01–1.07)**	1.00 (0.99–1.01)	**1.14 (1.01–1.27)**	1.00 (0.97–1.02)	0.97 (0.93–1.04)	0.92 (0.84–1.01)
Some days during a year						
Dry cough without cold	**1.05 (1.01–1.10)**	1.00 (0.99–1.01)	**1.23 (1.06–1.45)**	1.00 (0.97–1.03)	0.98 (0.92–1.05)	0.89 (0.79–1.00)
Phlegm	**1.06 (1.01–1.11)**	1.00 (0.99–1.01)	1.17 (0.99–1.39)	0.97 (0.93–1.02)	1.02 (0.94–1.10)	0.93 (0.81–1.07)
Clinical examination						
FeNO ≥ 30 ppb	**1.05 (1.01–1.09)**	**1.01 (1.00–1.01)**	**1.22 (1.06–1.41)**	**1.75 (1.17–2.62)**	0.94 (0.88–1.01)	**0.85 (0.75–0.96)**
FeNO ≥ 30 ppb and no asthma diagnosis	1.05 (1.00–1.10)	1.00 (1.00–1.01)	1.26 (1.06–1.50)	1.04 (1.01–1.07)	0.93 (0.86–1.01)	**0.81 (0.69–0.94)**

*Adjusted model for sex, age, BMI, parents' education and family income.

NMHC - non-methane hydrocarbons.

PM_{10} - particulate matter with a diameter between 2.5 and 10 micrometers (μm)

$PM_{2.5}$ - particulate matter with a diameter of 2.5 micrometers (μm) or less.

The odds ratios in bold are statistically significant ($p < 0.05$).

5.5.2 Effects on adults

People living in the highest quartile of the $PM_{2.5}$ levels had 1.13 (95% CI 1.02–1.26), 1.16 (95% CI 1.03–1.31) and 1.22 (95% CI 1.04–1.42) higher odds of reporting chest tightness, shortness of breath, and asthma attacks, respectively; compared to residents in the quartile of the lowest levels (Table 5). People living in areas with the highest quartile of the levels of benzene had 1.98 (95% CI 1.11–3.53) higher odds of having had a myocardial infarction in the past and people living in the quartile of the highest levels of phenol had increased odds of chest tightness (1.44, 95% CI 1.03–2.00), long-term cough (1.48, 95% CI 1.06–2.07), and myocardial infarction (2.17, 95% CI 1.23–3.83) (Table 5). Sensitivity analysis among the people who had been working in the oil shale sector showed a general increase in ORs, and differences appeared between Estonians and non-Estonians (Paper I).

Table 5. Odds ratios (95% CI) on disease prevalence per interquartile change in pollutant concentrations

	$PM_{2.5}$	Benzene	Phenol
During last 12 months*			
Wheezing without cold	1.03 (0.92–1.14)	1.06 (0.79–1.43)	1.36 (0.98–1.90)
Chest tightness	**1.13 (1.02–1.26)**	1.30 (0.96–1.76)	**1.44 (1.03–2.00)**
Shortness of breath	**1.16 (1.03–1.31)**	1.14 (0.80–1.62)	1.18 (0.80–1.74)
Attack of coughing	1.04 (0.94–1.15)	0.94 (0.71–1.24)	0.95 (0.70–1.30)
Asthma attack	**1.22 (1.04–1.42)**	1.14 (0.67–1.95)	0.60 (0.32–1.15)
Ever had*			
Wheezing	1.01 (0.99–1.22)	1.16 (0.86–1.56)	1.11 (0.80–1.55)
Long-term cough	0.99 (0.89–1.11)	1.31 (0.96–1.77)	**1.48 (1.06–2.07)**
Allergic rhinitis	1.07 (0.94–1.22)	0.92 (0.64–1.32)	0.89 (0.59–1.34)
Asthma	1.04 (0.87–1.24)	1.20 (0.70–2.06)	0.84 (0.45–1.56)
COPD	1.22 (0.84–1.76)	1.97 (0.72–2.10)	1.92 (0.71–5.19)
Hypertension	1.10 (0.98–1.24)	1.15 (0.83–1.59)	1.21 (0.84–1.74)
Heart disease	1.12 (0.98–1.28)	1.24 (0.83–1.84)	1.30 (0.84–1.98)
Myocardial infarction	0.99 (0.80–1.22)	**1.98 (1.11–3.53)**	**2.17 (1.23–3.83)**
Stroke	1.01 (0.76–1.35)	1.39 (0.62–3.11)	1.14 (0.50–2.62)
Diabetes	1.01 (0.85–1.21)	1.42 (0.86–2.34)	1.33 (0.78–2.27)

* Logistic regression analysis was adjusted for gender, age, body mass index (BMI), education, environmental tobacco smoke, smoking history, and income during past 12 months; COPD: Chronic obstructive pulmonary disease. Values in bold are statistically significant ($p < 0.05$).

5.6 Annoyance and health complaints (Paper I)

The prevalence of high annoyance due to air pollution (respondents who rated 7–10 on a 10-point scale, ranging from no annoyance (1) to very high annoyance (10)) significantly differed between the regions (Table 6). Respondents (both males and females) from Ida-Viru County were statistically significantly more annoyed by air pollution then those from Lääne-Viru and Tartu Counties.

Residents in Ida-Viru County who had experienced chest tightness during the last 12 months and had ever had wheezing, allergic rhinitis and asthma were significantly more annoyed by air pollution than those living in other regions. As for the effect of ethnicity, there were no regional differences in the frequency of annoyance among non-Estonians. However, Estonians in Ida-Viru County Estonians were significantly more annoyed than non-Estonians (Table 6).

Table 6. High annoyance (%) due to air pollution* per gender, ethnicity, and health problems of people in Ida-Viru County and the control regions (Lääne-Viru and Tartu), and regional comparisons

	Ida-Viru County	**Lääne-Viru County**	**Tartu County**	**Chi^2**	***p* Value**
Gender					
Males	22.4	14.9	11.8	36.70	**0.000**
Females	25.5	15.6	13.2	28.25	**0.006**
Ethnicity					
Estonians	18.5	13.7	10.0	13.70	**0.001**
Non-Estonians	24.2	17.9	21.9	0.85	0.655
Self-assessed health status					
Very good	14.3	23.1	6.1	6.17	**0.046**
Good	17.3	7.2	10.1	9.70	**0.008**
Average	21.5	16.2	17.2	1.74	0.420
Bad	37.9	10.9	27.0	1.37	0.504
Very bad	20.0	0	0	35.50	0.000
During last 12 months*					
Asthma attack	33.3	40.0	21.4	2.27	0.321
Chest tightness	36.6	27.0	22.9	8.46	**0.015**
Shortness of breath	38.4	34.8	28.8	2.49	0.288
Ever had*					
Wheezing	34.0	22.9	21.7	7.80	**0.020**
Long-term cough	28.9	25.0	19.8	4.82	0.090
Allergic rhinitis	25.8	18.8	15.3	6.54	**0.038**
Asthma	31.7	36.4	12.3	8.02	**0.018**
COPD	30.0	33.3	30.0	0.01	0.993

* Respondents who rated 7–10 on a 10-point scale, ranging from no annoyance (1) to very high annoyance (10).

As for the effects of education, compared to the other regions, Ida-Viru County had significantly more respondents annoyed by air pollution among people with a secondary or higher education (Table 7). As per the effect of income, the differences in annoyance appeared only among the highest income group, with wealthy people in Ida-Viru more frequently annoyed than those in Lääne-Viru and Tartu.

Table 7. Association between specific factors, air pollutants and the prevalence of annoyance in the three investigated counties, odds ratios (95% CI).

	Ida-Viru County	Lääne-Viru County	Tartu
Males *(ref females)*	**0.64 (0.42–0.97)**	1.01 (0.36–2.88)	**0.64 (0.41–1.00)**
Secondary education *(ref applied or higher)*	0.87 (0.56–1.34)	0.66 (0.21–2.04)	1.21 (0.78–1.87)
Income	1.08 (0.91–1.27)	1.17 (0.74–1.85)	0.89 (0.75–1.05)
Current or ex-smokers	0.89 (0.70–1.13)	0.50 (0.24–1.05)	1.04 (0.82–1.35)
Self-rated health status	**1.59 (1.21–2.08)**	**2.56 (1.23–5.36)**	**1.49 (1.13–1.97)**
Pollutants*, #			
$PM_{2.5}$	1.07 (0.94–1.22)		
Benzene	1.04 (0.87–1.24)		
Phenol	1.22 (0.84–1.76)		
During last 12 months*			
Wheezing without cold	**2.30 (1.31–4.04)**	0.11 (0.01–0.92)	0
Chest tightness	**2.88 (1.91–4.33)**	**3.19 (1.02–9.92)**	**2.26 (1.36–3.74)**
Shortness of breath	1.60 (0.92–2.79)	94.83 (3.35–2680.68)	**3.24 (1.88–5.57)**
Attack of coughing	**1.99 (1.34–2.95)**	2.10 (0.75–5.84)	**1.57 (1.03–2.38)**
Asthma attack	1.48 (0.79–2.77)	4.83 (0.79–29.35)	2.16 (0.98–4.75)
Ever had*			
Wheezing	**1.98 (1.31–2.99)**	1.52 (0.48–4.82)	**1.81 (1.13–2.90)**
Long-term cough	1.29 (0.86–1.94)	3.04 (1.01–9.16)	**1.92 (1.21–3.05)**
Allergic rhinitis	1.40 (0.82–2.37)	1.36 (0.34–5.45)	1.34 (0.78–2.27)
Asthma	1.18 (0.60–2.32)	2.85 (0.6–13.61)	1.36 (0.65–2.85)
COPD	1.69 (0.56–5.14)	6.21 (0.16–246.71)	3.18 (0.78–12.8)
Hypertension	1.05 (0.68–1.63)	1.13 (0.35–3.69)	1.12 (0.51–2.47)
Heart disease	1.22 (0.61–2.42)	7.81 (1.41–43.16)	0.47 (0.16–1.39)
Diabetes	0.67 (0.35–1.29)	0.47 (0.04–4.84)	0.83 (0.09–6.96)

* Logistic regression analysis was adjusted for gender, age, BMI, education, environmental tobacco smoke, smoking history, and income during past 12 months.
# Annoyance prevalence per interquartile change in pollutants concentrations.
Values in bold are statistically significant ($p < 0.05$).

Regarding self-rated health, people with good health were more frequently annoyed by air pollution in Ida-Viru County compared to the other regions (Table 7). In all regions the odds of being annoyed increased significantly when a person had chest tightness. In Ida-Viru region, the odds of being annoyed increased significantly when a person had symptoms such as wheezing without a cold, attacks of coughing, and diagnosed wheezing. In Tartu, the odds of being annoyed increased when a person had shortness of breath, attacks of coughing, wheezing and a long-term cough. Due to the lack of data, the effect of air pollution exposure in other regions except Ida-Viru County was not calculated (Table 7).

5.7. Cancer incidence among residence (Paper III)

The total registered numbers of observed cancer cases between 1992–2015 in Estonia and Ida-Viru County were 51,525 and 6,752, respectively. The mean age at diagnosis of lung cancer, breast cancer, kidney cancer, urinary bladder cancer, non-Hodgkin's lymphoma, and leukaemia were 67, 62, 65, 70, 63, and 63 years in Estonia on average and 66, 60, 64, 68, 59, and 62 years in Ida-Viru County, respectively (Paper III).

Age-standardised incidence rates (ASIR) among observed cancer sites have increased from 1992 to 2015 among both males and females. The incidence rates in females in Estonia for lung cancer, kidney cancer, urinary bladder cancer, non-Hodgkin's lymphoma and breast cancer rates have increased two-fold during the period (Figure 5). Additionally, ASIR for lung cancer and non-Hodgkin's lymphoma have increased two-fold in oil shale areas. However, the increase in oil-shale areas does not reach statistical significance when compared to the national average in Estonia.

A statistically significant increase in the ASIR in the oil shale area was found for lung cancer in males. Nationally, the ASIR for male lung cancer increased by 1.5% between 1992 and 2015. In non-oil shale areas, this increase was more pronounced at 13.3% (increase statistically significant, $p < 0.05$), whereas a statistically significant decrease of 28.9% ($p < 0.05$) was observed in the oil-shale area. Despite this downward trend, the ASIR for lung cancer among males in the oil shale area remains higher than in both non-oil shale areas and the national average. Among females, the ASIR for lung cancer in the oil shale areas increased from 17.6 per 100,000 person-years in 1992 to 34.2 per 100,000 person-years in 2015, corresponding to a growth index +94%. The growth rates in Estonia overall and in the non-oil shale areas have been even larger: 109% and 181% (increase statistically significant), respectively.

The overall ASIR trend for kidney cancer among males increased both in Estonia and in the non-oil shale area and was statistically significant ($p < 0.05$) in the non-oil shale area compared to Estonia. The ASIR for kidney cancer in males was higher in the oil shale area at the beginning of the period (1992) but was lower than national average at the end of the study period (2015). The ASIR for urinary bladder cancer in males increased in both Estonia overall and the oil shale areas, while a decrease was observed in the non-oil shale area; however, these differences were not statistically significant. The ASIR for non-Hodgkin's Lymphoma increased across all three observed areas without statistically significant difference between them. The ASIR for leukaemia in males had increased during the last two decades (1992–2015) in Estonia and in non-oil shale areas. However, the ASIR had been lower in the oil shale areas than in Estonia overall.

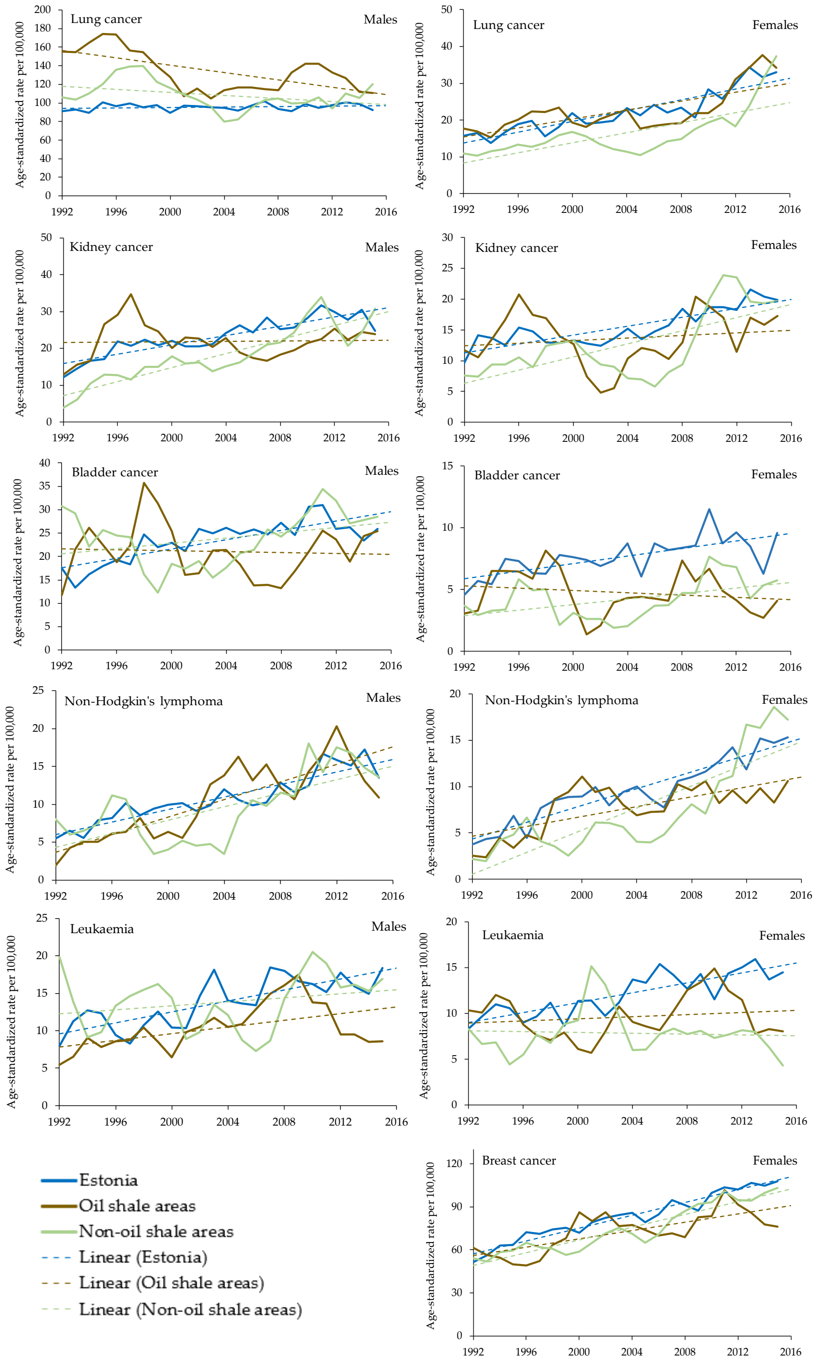

Figure 4. Age-standardized incidence rates for cancer sites in oil shale (brown line) areas, non-oil shale (green line) areas and Estonia overall (blue line). Cancer trendlines are represented with dashed lines.

Among females, the ASIRs for kidney cancer and non-Hodgkin's Lymphoma increased in non-oil shale areas and were significantly higher compared to the national average. The ASIR for urinary bladder cancer in females had doubled in Estonia between 1992 and 2015, from 4.6 to 9.6 per 100,000 person-years. The increase was smaller in the oil shale areas, from 3.1 to 4.1, and in the non-oil shale areas, from 3.7 to 5.7, but the trend is still statistically significant. The incidence rates for leukaemia among females during that period had increased in Estonia, however declined significantly ($p < 0.05$) in both oil shale and non-oil shale areas, decreasing from 10.3 to 9.1 and from 8.3 to 4.3 cases per 100,000 person-years, respectively. Among females, the ASIR for breast cancer increased at an average of 1.5% per year in the oil shale areas, 3.1% per year in the non-oil shale areas, and 3.5% per year over the period in Estonia overall. The incidence rates for breast cancer in females have been higher in Estonia overall and in the non-oil shale areas than in the oil shale areas.

6. DISCUSSION

The current thesis aimed to identify the air quality situation in Ida-Viru County, to study possible relationships between (oil shale) industry-specific air pollutants and the respiratory health of children and the health of local residents as well as to investigate cancer incidence trends in oil shale industrial areas in Estonia, and people's annoyance regarding air pollution.

The two cross-sectional studies, based on a large sample, show that compared to the control groups from non-industrial areas in Tartu or Lääne-Viru County, Ida-Viru County residents more frequently report wheezing, chest tightness, shortness of breath, asthma attacks, a long-term cough, hypertension, heart diseases, myocardial infarction, stroke, and diabetes. People living in regions with higher levels of $PM_{2.5}$, benzene, or phenol had higher odds of experiencing chest tightness, shortness of breath, or an asthma attack during the previous year and a long-term cough or myocardial infarction in the past. Also, the lung cancer incidence rate was statistically higher in Ida-Viru County than in other investigated counties; however, this effect did not appear for other cancer sites. The prevalence of symptoms commonly associated with asthma and asthmatic symptoms was higher among 8–12-year-old children in industrially-exposed Ida-Viru County compared to the non-industrially-polluted Tartu region. The prevalence of adverse health effects was also higher among those who had been working in the oil shale sector.

6.1. Exposure assessment

Measuring and modelling air pollution and performing exposure assessments are essential in evaluating the environmental state in broader areas. If we compare the air quality in the cities of Ida-Viru County with the capital, Tallinn, the situation is generally similar in terms of traditional pollutants. However, the main problems of the urban air in Ida-Viru County are related to region-specific pollutants, such as hydrogen sulphide, which often exceeds the hourly average limit value of the pollution level (EKUK, 2023).

In general, the applied air pollution dispersion model performed for Ida-Viru County was rather well compared to measured values in monitoring stations (Paper I, II). The temporal variation of the model was good, but it somewhat underestimated the $PM_{2.5}$ and phenol levels in Narva and vastly underestimated benzene levels in Sillamäe. Also, there appeared to be spatial variation, as the concentrations were higher close to oil shale industry facilities. However, the variations were different for different pollutants and locations, e.g., close to Kiviõli, there appeared to be high concentrations of phenol but low concentrations of benzene and vice versa in Kohtla-Järve.

The analysis showed a clear problem of industrial pollutants, including benzene, phenol, and hydrogen sulphide. The primary sources of industrial emissions from benzene and phenol are shale oil processing and energy production. Due to the more restrictive environmental protection requirements and investments in new technologies and treatment facilities, exceedances have decreased in recent years. Also, the concentrations of benzene, polycyclic aromatic hydrocarbons, and heavy metals in the ambient air have considerably diminished compared to earlier studies (Teinemaa et al., 2017). However, the exceedances that still occur need proper addressing by the industry and regional authorities. Sometimes, the problems have not been fully acknowledged, e.g., ambient air quality has been an issue for years in Kiviõli. However, national monitoring could not reflect the problem as there was no monitoring station for several years (Pihor et al., 2013). Since February 2021, there has been a monitoring station in a residential area in Kiviõli. During three years, there have been, on average, seven exceedances of industry-specific pollutants like H_2S during a year (EKUK, 2024). Unfortunately, this station is not included in the air pollution national monitoring system; hence, there are no regular analytical reports from this station despite it being of regional importance (Riigi Teataja, 2023).

According to our air pollution dispersion models, based on emission data, high phenol concentrations in Kiviõli have been to be expected (Figure 1). At a nearby distance (~1 km) from the oil shale chemical and energy complex in Kiviõli and Kohtla-Järve, increased concentrations of phenols, NO_2, H_2S, SO_2, dust, Pb, benzene, formaldehyde, etc., have also been observed earlier (Этлин, 1989). Phenols, as well as other oil shale chemical products have been shown to be toxic in several studies (Babich and Davis, 1981; Kahn, 1979).

The strengths of the exposure assessment in the research were the air pollution dispersion modelling, with a large number of different industry- (including oil shale industry) specific pollutants, such as benzene, phenol, formaldehyde and NMHC. Typically, only core pollutants, such as $PM_{2.5}$, SO_2 and NO_X, are studied (Bergstra et al., 2018; Brand et al., 2016; Sarić-Tanasković et al., 2006; S. Wong et al., 2016). Dispersion modelling considers stack height, annual weather conditions and the exact location of subjects' (children and adults) home addresses. Many studies of industrially contaminated areas have only compared resident populations with control areas or have relied on emission information instead of modelled exposure patterns.

The limitations of the research exposure assessments were as follows. Firstly, the emission-based exposures were only calculated for one year (2013), as no information was available on the subjects' previous residences. There is still little known about long-term exposure to low-level air pollution. Recent studies from Sweden (Sommar et al., 2021), Denmark (Hansen et al., 2016; So et al., 2022), England and Wales (Hansell et al., 2016) have shown that long-term exposure to low-level air pollution is associated with increased mortality. Effects of air pollution persist decades after exposure; air pollution over time may be more harmful than anticipated (Xu et al., 2023) and therefore needs to be investigated more. Secondly, the emission data in some cases was of low quality, which caused the heterogeneous deviation of some concentrations of pollutants, even in the chemical industry region.

There is evidence that people, especially children living near (i.e. within 5 km) industrial sites or are exposed to industrial pollutants, have an increased risk of adverse health outcomes when compared with those living far away (i.e. 20 km) or those less exposed (Alwahaibi and Zeka, 2016; Bergstra et al., 2018; Lewin et al., 2013; Nirel et al., 2014; Smargiassi et al., 2014; Wichmann et al., 2008; Wilhelm et al., 2007; C. M. Wong et al., 2016; Yang et al., 1997) (Paper II). Therefore, for the analysis, children living within a 5 km radius of a shale oil industry site or a power plant were considered as exposed to industrial pollution, compared to subjects living in the rest of Ida-Viru County. Cities of Kohtla–Järve (Järve district), Kiviõli and Püssi (termed the ʻChemical industry region') were considered to be highly exposed to industrial pollutants. Respondents from the ʻChemical industry region' and from the city of Narva, which has two electricity generation plants using fuel extracted from oil shale located nearby (termed the ʻChemical industry and power plant region'), were considered to be highly exposed to industrial pollutants.

For the ecological study on cancer incidence in the industrialised area, the municipalities in Ida-Viru County were divided into those with a greater degree of exposure to industrial pollution (termed the ʻoil shale areas') and less exposure to industrial pollution (termed the ʻnon-oil shale areas') based on Geological Survey of Estonia data on the mines, the locations of industrial sites, and Population Register data on people's places of residence at the time of cancer diagnosis. In order to gain better exposure assessment, there is a need for detailed and linked data of the person's cancer diagnosis, living address, and socio-economic situation, including their education or salaries. However, the linking was not possible due to data protection regulations at that time. Therefore, associations between cancer incidence and industrial pollution could be only indirectly linked as, at the time, we lacked information about personal exposure, such as dosage and time, due to difficulties with people's identification codes.

Annoyance by environmental exposure has been suggested to serve as an early warning signal of illness already thirty years ago (Baird et al., 1990). Analysis has proved that annoyance from air pollution is related to subjective health concerns and respiratory symptoms, e.g., chest tightness, wheezing or cough. This suggests that annoyance may lead to health complaints. However, the relationship may also work the other way around: symptoms may sensitise individuals to pay more attention to air pollution. Nevertheless, annoyed Ida-Viru people have more frequent respiratory problems than people in other regions, suggesting that annoyance is associated with the objective conditions in the oil shale region.

The environmental condition in Ida-Viru County has improved considerably over the last decades. To improve the ambient environment, oil shale mining companies and shale oil extraction facilities have implemented new, more environmentally friendly production technologies (Viru Keemia Grupp, 2010). Additionally, there has been an overall decrease in annual average levels of hydrogen sulphide in both Kohtla-Järve and Narva (Saare, 2024). Restrictive environmental legislation, especially for large industries has made a big impact on it. In order to achieve the goals, several action plans have been put in place for different companies to abate odour, air pollution and noise in the area (Keskkonnaamet, 2024). The Environmental Board monitors implementation plans. Furthermore, there is enormous pressure on industries in communities to have cleaner air and cleaner environments as they have become more environmentally conscious and ask for better living conditions than years before.

6.2 Respiratory health

Higher proportions of air pollutants within a short-term period cause several acute respiratory effects like mild irritations, inflammations, allergic reactions, and sometimes complete respiratory failures that lead to increased numbers of emergency room visits, hospitalizations, and deaths (Bell et al., 2009; Brunekreef and Holgate, 2002; Rich et al., 2019; Samoli et al., 2016; Xia et al., 2017). Whereas long-term exposure to air pollutants has been indicated to have a direct relationship with developing chronic respiratory diseases like asthma and chronic obstructive pulmonary disease (COPD) (Adam et al., 2015; Anderson et al., 2012; Doiron et al., 2019; Jacquemin et al., 2012; Li et al., 2003; Zanobetti et al., 2008).

6.2.1 Children

Research on chemical exposure to the oil shale industry is still quite rare, and therefore, there is little information on possible health outcomes for children living close to shale oil extraction sites. The prevalence of symptoms commonly associated with asthma and asthmatic symptoms was higher among 8–12-year-old children in Ida-Viru County compared to the non-industrially-polluted Tartu region. Despite the relatively small number of studies focussing on the respiratory symptoms of children living near petrochemical industries, it has been shown that exposure even to low levels of atmospheric pollutants such as benzene, NO_2 and PM_{10} is associated with an increase in wheezing symptoms, decrease in lung function, a nocturnal cough and a higher prevalence of respiratory hospitalizations (Moraes et al., 2010; Rovira et al., 2014; Rusconi et al., 2011).

In the current research, a similar trend for benzene was observed, but there was no association for PM_{10}, and the reverse trend was seen for $PM_{2.5}$. The main reason for this could be the different sources of the pollutants. Benzene, phenol, formaldehyde, and non-methane hydrocarbons are mainly industry-based, whereas a large proportion of particulates come from traffic (Maasikmets et al., 2013). It also appears that children with asthma and with a high risk of air pollution are those who live near the sources of industrial pollutants; they often have the least access to medical care due to poverty (Gold and Wright, 2005). Meanwhile, children living in larger cities, with higher levels of fine particles, have better access to medical care and may have lower FeNO values (Petsky et al., 2016).

The analysis also showed that the prevalence of asthma and asthmatic symptoms in Estonia has increased over time (Meren et al., 2001; Vasar et al., 2011). According to questionnaire-based studies on children's health, the prevalence of asthma diagnosis by a physician after the collapse of the Soviet Union in the 1990s was only 2.4% in Narva (the largest city in Ida-Viru County) (Meren et al., 2001); however, these studies also reported numerous respiratory symptoms indicative of mild asthma. By 2003, the prevalence of asthma in Narva among preadolescent children had increased to 5.2% (Vasar et al., 2011). The SOHOS study showed that asthma in Narva had doubled since 2003, and the overall prevalence in Ida-Viru County was approximately 2.5 times higher. However, some of the differences between periods may be the result of differences in asthma diagnosis. Until the beginning of the 1990s, the definitions of chronic respiratory diseases accepted in the Soviet Union were used in Estonia; the definition of asthma was characterised by symptoms such as bronchospasm, hypersecretion, breathlessness and swelling of bronchial mucosa (Jannus et al., 1975). Asthma was often considered to be a complication of a chronic bronchitis or even chronic pneumonia (Ado, 1978) rather than actual disease.

One of the established biomarkers of airway inflammation, FeNO (Ricciardolo et al., 2015; Van Amsterdam et al., 2000), was measured during our clinical examinations. Measuring fractional nitric oxide as a biomarker of poor respiratory health was a relatively novel method for detecting undiagnosed and untreated asthma when we implemented it. Detecting asthma and pre-asthmatic conditions using FeNO was already in use in several Nordic studies in the early 2000s (Lassmann-Klee et al., 2020).

According to the guidelines of the American Thoracic Society, the cut of values of FeNO for children are 20–35 ppb (Dweik et al., 2011). Values higher than 35 ppb state a clear eosinophilic airway inflammation present, and one would most probably benefit from inhaled corticosteroid. In the current analysis, high FeNO levels were defined as ≥ 30 ppb, as previously described by Pijnenburg et al. (2005) and Wang et al. (2017). The values were lowered considering the local clinical context. The prevalence of high FeNO levels (i.e. ≥ 30 ppb) in Ida-Viru County was 3.8 times higher than in Tartu and 1.8 times higher than in Lääne-Viru County. Furthermore, a large proportion of children had high FeNO values but no (self-reported) asthma diagnosis by a physician. This is a significant public health concern, as high levels of FeNO indicate for bronchodilator responsiveness and probable asthma (Malmberg et al., 2003).

Children living within a 5 km radius of a shale oil chemical plant and/or a power plant using fuel extracted from oil shale also had 1.63 (95% CI 1.03–2.60) higher combined odds of having high FeNO values than children living further away. Several studies (Fischer et al., 2002) investigating associations between fractional exhaled nitric oxide, ambient air pollution and respiratory health in schoolchildren confirm the observation of an association between air pollution and higher levels of FeNO in children (Fischer et al., 2002; Flamant-Hulin et al., 2009).

The main strength of the research was the determination of using FeNO levels as the respiratory inflammation marker to diagnose asthma or define a pre-asthmatic situation. It has been proven earlier to be a good diagnostic tool for detecting mild-asthma and pre-asthmatic situations by specialists and, therefore, starting the treatment in the early stages (Fischer et al., 2002). Even though the asthma prevalence in Ida-Viru County has risen a little by the year 2019 (from 13.0 to 13,8%) but there were significantly fewer children with high FeNO levels (≥30 ppb). Recognition of respiratory health problems and treating them at an early stage of the disease development has contributed to decreasing severe respiratory health problems among children in the region in later years (Veber et al., 2021).

The main limitation was that the data on health symptoms and diseases was self-reported. Also, living in an industrial area may be viewed as a health threat (Paper II); families with asthmatic children may avoid living near contaminated sites or may move away. Although, oil shale-related air pollutants (especially benzene) were associated with respiratory symptoms, self-reported physician-diagnosed asthma together with clinically measured FeNO values.

6.2.2 Adults

The cross-sectional study (Paper I) based on a large sample, showed that compared to the control groups from non-industrial areas in Tartu or Lääne-Viru County, Ida-Viru County residents reported more frequent wheezing, chest tightness, shortness of breath, asthma attacks, a long-term cough, and other communicable diseases. In this study, the observed people living in Ida-Viru County in areas with higher levels of $PM_{2.5}$, benzene, or phenol had significantly higher odds of reporting several respiratory diseases and myocardial infarction. Similar associations were documented in the same region more than 25 years ago by Etlin (Этлин, 1989).

The increased risk of respiratory diseases has also been shown in industrial areas in China if residents were living close to a factory or chimney (Wilson et al., 2008), as well as among residents living in high-industry areas in Port Adelaide, Australia (Pilotto et al., 1999). In a Canadian study, Fung et al. showed an increased risk of respiratory as well as cardiovascular disease in industrial cities compared to a reference city, with higher standardised hazard ratios among women (Fung et al., 2007). In an ecological study of an industrial area in France, Pascal et al. did not find a higher risk of hospitalisation due to respiratory diseases (L. Pascal et al., 2013). If we compare our findings with other studies, there is an extensive amount of evidence of the adverse health effects of $PM_{2.5}$ on the respiratory system (Bourdrel et al., 2017; Xing et al., 2016); but there is substantially less evidence of the effects upon health of benzene (Bahadar et al., 2014; Fenga et al., 2016) and phenols (Umweltbundesamtes, 2011), especially in ambient air, often because of a lack of monitoring data to enable epidemiological studies.

The current study (Paper I) indicated that working in the oil shale industry also poses an occupational risk. Respondents who had been working in the oil shale sector had a significantly higher prevalence of respiratory and cardiovascular diseases. One reason could be higher benzene concentrations, which are twice as high in mines compared to other production units (Sorensen et al., 2004). As the ventilation systems in the mines are weak and raw material is handled with machines using diesel fuel, mine workers had a much higher exposure to benzene than those who worked on the ground (Sorensen et al., 2004). Exposure to diesel engine exhaust gases has also caused porphyrin and heme metabolism alterations in miners' peripheral lymphocytes (Muzyka et al., 2004). This may refer to weakening immune mechanisms in people exposed to industrial air pollution components, and such chronic exposure might cause significant disorders in heme synthesis and metabolism (Viitak et al., 2004).

Health issues are usually the main reason mine workers leave the job because, according to miners, the damage to their health is often so extensive that they cannot continue working in the mines (Murakas et al., 2012). Earlier studies have shown mine workers to be exposed to high dust levels (Tint, 1998) and often they had pulmonary diseases caused by inhaling dust (Küng, 1979). Better self-protective equipment is generally used, but people retiring during the study years or who are presently disabled were still exposed to high concentrations of pollutants during the 1970s–2000s.

The main limitations of the study include the cross-sectional nature of the investigation, using only current exposure and self-reporting of health-related symptoms and illnesses. In addition, in questionnaire studies, native residents, females and older people tend to answer more frequently. Therefore, future studies could also include children to see the effect of the current environmental situation on respiratory health. Methodological developments, e.g., medical screening in combination with interviews, could be employed to avoid underreporting the adverse effects of community pollution by people working in the industry. Whereas the use of control areas was a clear strength of the current study, in future analysis, it would be worth investing in gathering data to validate the samples with the health characteristics of the general population and use health registers data.

6.3 Cardiovascular health

People living in regions with higher levels of $PM_{2.5}$, benzene, or phenol had higher odds of experiencing chest tightness, shortness of breath during the previous year and myocardial infarction in the past. The prevalence of adverse health effects was also higher among those who had been working in the oil shale sector.

In this study, we observed that people living in Ida-Viru County in areas with higher levels of $PM_{2.5}$, benzene, or phenol had significantly higher odds of reporting myocardial infarction but no other cardiovascular disease. Similar relationships were documented in the same region more than 35 years ago by Etlin (Этлин, 1989).

In a Canadian study, Fung et al. showed an increased risk of cardiovascular disease in industrial cities compared to a reference city, with higher standardised hazard ratios among women (Fung et al., 2007). In an ecological study of an industrial area in France, Pascal et al. found a higher risk of hospitalisation due to myocardial infarction (L. Pascal et al., 2013). In contrast, in England and Wales, Aylin et al. did not show any increased risk of hospitalisation due to cardio-respiratory diseases among a population living near coke works (Aylin et al., 2001). If we compare our findings with existing studies, there is a significant amount of evidence of the adverse health effects of $PM_{2.5}$ on the cardio-respiratory system (Bourdrel et al., 2017; Xing et al., 2016).

The standardised mortality rate (SMR) of cardiovascular diseases in Ida-Viru County has been higher than elsewhere in Estonia during the last eighteen years (Tervise Arengu Instituut, 2024b). Even though the SMR of cardiovascular diseases has decreased enormously in Ida-Viru County since 2005, almost half (from 1034 to 644 (2022)), it is still 10% higher than average in Estonia (575), being highest among Estonian Counties (Tervise Arengu Instituut, 2024b).

6.4 Diabetes

The diabetes prevalence was significantly higher among those who had worked in the oil shale sector compared to those not working in the sector, being more frequently reported among non-Estonians. Similar associations were documented in the oil shale region more than 25 years before by Etlin (Этлин, 1989). However, a high prevalence of diabetes has been shown in industrial employees of southern Poland (Wittek et al., 2009) and among petroleum refinery workers in Iran (Hosseininejad et al., 2021).

However, people living in Ida-Viru County in areas with higher levels of $PM_{2.5}$, benzene, or phenol did not have higher odds of reporting diabetes. If we compare our findings with existing studies, there is a very significant amount of evidence of the adverse health effects of $PM_{2.5}$ as a cause of diabetes worldwide (Esposito et al., 2016; Hansen et al., 2016), including a recent systematic review (Yang et al., 2020) of 86 studies that strengthened the evidence for adverse effects of $PM_{2.5}$ on diabetes. Ren et al (Ren et al., 2023) performed a systematic review of 35 epidemiological studies covering almost 7 million pregnant women, showing that fine particulate matter and other air pollutants were associated with gestational diabetes mellitus.

Identifying diabetes among residents could be one of the limitations as it was self-reported and not objectively measured by glycose level, etc., urine and blood samples that are needed in order to identify metabolic disorders.

6.5 Cancer incidence

In this study, we investigated cancer incidence trends in oil shale industrial areas in Estonia. We focused on cancer sites that could be related to industry-specific pollutants in an industrialised region in North-East Estonia. In the current study, we could see a higher ASIR only for lung cancer in the oil shale industrial areas as compared to the non-oil shale areas and Estonian average. Lung cancer is one of the leading causes of cancer-related morbidity and the most common cause of cancer-related mortality in males in Estonia (Ferlay et al., 2018). Even though the incidence rates for lung cancer in males have decreased in oil shale areas, the incidence of lung cancer in those areas was higher during the study period compared to the Estonian average and the rest of Ida-Viru County.

During an earlier analysis in 1989, Etlin (Этлин, 1989) presumed that cancer incidence would increase if ambient air pollution increased. However, since the 2000s, air quality has improved noticeably in the industrial region of Estonia (as reported by the monitoring station in Kohtla-Järve) (K Orru et al., 2015). During the same period, we could see a decrease in lung cancer incidence rates, and even though we cannot justify the causal relationship with the current ecological study design, the associations are possible.

Higher incidence rates of lung cancer could also be associated with occupational exposure. Several earlier studies (Attfield et al., 2012; Gamble et al., 2012; Gustavsson et al., 2000; Kim et al., 2018; Richiardi et al., 2006; Silverman et al., 2012) have shown that long-term occupational exposure to high levels of diesel exhaust is associated with an increased risk of lung cancer. As of 2015, there were 16% of males in Ida-Viru County, who were occupied in the oil shale industry, where diesel fuel is used to power the machines, they could therefore be at a higher risk of developing lung cancer. The indications of increased cancer morbidity risk could also be found from earlier biomonitoring studies among oil shale mining employees, who showed increased benzene metabolites excretion (Sorensen et al., 2004), increased porphyrin metabolism in lymphocytes (porphyrin associated with DNA increased 1.4-fold) (Muzyka et al., 2002), and an increased level of DNA damage as a higher number of DNA adducts (Knudsen et al., 2005). As the Estonian Cancer Register does not record occupational information, we could not analyse the effects of occupational exposures.

Still, we must admit that the trends in lung cancer incidence are as likely to be influenced by past smoking prevalence than by environmental factors. Past smoking prevalence in males, particularly in populations with less education, has been high. According to the Estonian Health Behaviour Survey (Tekkel and Veideman, 2017), the daily smoking prevalence in males in the 1990s was around 50% and has decreased since 2006. Therefore, some of the lung cancer incidence could be attributable to smoking habits, as a large number of males are exposed to direct or indirect contact with tobacco smoke daily in Ida-Viru County in the oil shale industrial areas (Tekkel and Veideman, 2017). The significant effect of smoking was also shown in earlier biomonitoring studies (L. E. Knudsen et al., 2005; Muzyka et al., 2004), in which the level of DNA damage in underground workers was significantly higher in smokers than in non-smokers. Silverman et al. (Silverman et al., 2012) have also shown a combined effect as the cumulative exposure to tobacco smoke and diesel exhaust among males working in industries is increased threefold from that of non-smoking workers. We propose that the recent decreasing trend of lung cancer in males in the oil-shale areas could be the combined effect of positive changes in environmental exposure as well as past smoking habits.

In our study, we could also see increased lung cancer incidence rates in females in all areas. Aareleid et al. (Aareleid et al., 2017) have suggested that this increase in Estonia is attributable to an increased rate of female tobacco smoking. Estonian females have always had a lower prevalence of smoking than males, but smoking among females increased in the 1990s (Tekkel and Veideman, 2017). With a latency period of 20 years for lung cancer, the increase in tobacco smoking prevalence among females could explain the increasing trend of lung cancer incidence for females.

Another lung cancer risk factor prevalent in the area is radon. The main health damage caused by inhaling radon and its degradation products is lung cancer, which causes 3%–20% of all cases worldwide (Dobrzynski et al., 2018; Oh et al., 2016; Yoon et al., 2016). According to Petersell et al. (Petersell et al., 2017b), in 1/3 of the Estonian territory, including Ida-Viru County, the radon risk exceeds the limit considered safe for unrestricted construction, i.e., 50 kBq/m3. Due to the lack of personal-level data on radon exposure, and as exposure exceeding safe levels is prevalent in large areas, we could not consider this effect. Nevertheless, the multiple and heterogeneous human exposures associated with these industrially contaminated sites assess possible lung cancer causes a challenging endeavour.

An ageing population, better diagnostics, and increased screening have increased the overall incidence of cancer cases worldwide, and this is also the case in Estonia, including in Ida-Viru County (Zimmermann et al., 2017). The upward trend of breast cancer in Estonia is similar to other developed countries. It could be due to increased screening and early detection as a result of the introduction of the Breast Cancer Screening Program in 2002 for women 50–69 years (Ulp et al., 2010). However, the screening quality might vary, as Innos et al. (Innos et al., 2011) have shown a higher risk of advanced breast cancer diagnosis in the studied industrial area compared to two major Estonian cities, Tallinn and Tartu. Nevertheless, in contrast to earlier findings (Adegoke et al., 2003; Cong, 2018; Iavarone et al., 2018; Stenehjem et al., 2014), no evidence of increased incidence rates of bladder cancer, kidney cancer, non-Hodgkin's lymphoma, or leukaemia was detected among those living or working in an industrial area of Estonia. According to common environmental health practices and similar previous environmental impact studies (Iavarone et al., 2018; Pirastu et al., 2013a), incidence is considered more appropriate for assessing relationships between morbidity and environment. Therefore, we used cancer incidence instead of survival, as cancer survival is more dependent on the functioning of the health care system and less on the environment, and the findings might bias the actual situation.

Other explanations could be lifestyle-related factors such as obesity, hypertension, smoking, and alcohol consumption, which are quite widespread and unequally distributed. These factors definitely play a role in the emergence of cancer in the studied populations and could have masked the effect caused by oil-shale mining in the studied areas. Unfortunately, we did not have data on these possible confounders.

If we take a look at the public health status of the population in Ida-Viru County, it is in many ways worse than in the rest of the country (e.g., life expectancy is four years lower than in the capital area) (Lai and Leinsalu, 2015;

Metsoja et al., 2017). Several studies (Lai and Leinsalu, 2015; Leinsalu et al., 2008) have indicated that lower education could be an obstruction to better health-related behavioural choices. According to the 2011 and 2021 census (Statistics Estonia, 2022b, 2012), there were more people with lower education living in Ida-Viru County than elsewhere in Estonia. In 1998–2013, the highest age-standardised mortality rates for several causes of death were found in Ida-Viru County. Both males and females had higher mortality rates for HIV, injuries like accidental poisoning, exposure to narcotics (mainly illegal drugs), assault occurring mainly among young adults, and circulatory diseases that form from unhealthy lifestyle choices. As cancer is an aging-associated disease whose likelihood increases with age (White et al., 2014), the cancer ASIR could, therefore, be lower in industrially contaminated areas.

The morbidity rate for all cancers, except skin cancer, in Ida-Viru County from 2000 until 2009 was one of the lowest in Estonia and has since been gradually increasing, changing an average of 3.4% a year (Tervise Arengu Instituut, 2024b). On the other hand, the incidence rate of lung cancer has always been higher than average in Estonia. The standardised mortality rate (SMR) for all cancers in Ida-Viru County has been slightly lower than average in Estonia, increasing in recent years (Tervise Arengu Instituut, 2024b). People in Ida-Viru County suffer from cardiovascular diseases earlier than malignant neoplasms, while the trend of cancer morbidity in Ida-Viru County is increasing.

As for the limitations of the cancer study, first, there was no information on a number of factors that could confound the association between exposure and cancer outcome. Also, there is no information on the resident's occupational status or data on risk factors, as there is no collection of these data in the Cancer Register. For the long period under study, there was no information about behavioural risk factors like smoking, alcohol use, excess body weight, and hypertension. These data may be available in the future by linking with other sources.

Second, there was no information on residents' socio-economic situation, including their education or salaries. The earlier studies indicated slightly higher cancer incidence estimates for Russians than for Estonians. However, this variation is likely attributable to exposure to specific etiological factors caused by differences in hygiene, smoking, and drinking (Lang, 2009) in Ida-Viru County.

Third, associations between cancer incidence and industrial pollution could be addressed indirectly due to the lack of information about personal exposure, such as dosage and time.

Fourth, the descriptive, register-based study design may have not captured findings associated with environmental and occupational risks. The design issues relevant to this type of investigation have been thoroughly examined by Elliott and Savitz (Elliott and Savitz, 2008), more detailed description of the limitations of ecological study design is available from Pirastu et al. (Pirastu et al., 2013a, 2013b), Savitz (Savitz, 2012) and Wakefield (Wakefield, 2008). The primary constraint lies in the implicit assumption that residents in the industrial area experience similar exposures. In contrast, exposure variability is likely to be substantial due to many factors (e.g., distance of residence from polluting sources, occupation, lifestyle). Still, as suggested by Pirastu et al. (Pirastu et al., 2013a), to enhance this study design, we selected a rather long period and a sufficiently large population size. As the study's main strength, we used validated and high-quality data from the Estonian Cancer Register, which has complete population coverage.

In the future, a similar analysis should include as many combined risk factors as possible. From the perspective of public health individual-level data on confounding factors like smoking habits, lifestyle, socio-economic situation, migration, past exposures, occupations, and ambient conditions are essential to make regional and country-wide health policy decisions.

6.6 Perceived annoyance from environmental exposure

The physical environment in which individuals reside significantly influences their self-perception and overall life satisfaction. Despite its critical role, this influence has often been underappreciated, and its presence is taken for granted. For instance, the availability of clean air and potable water is fundamental to daily well-being and health. These essential elements typically garner attention only when severely compromised, such as during episodes of severe air pollution or disruptive noise levels. Annoyance from environmental exposure has been suggested to be an early warning signal of illness already in 1990 (Baird et al., 1990). Since then, people have started to recognize its value more extensively. According to the Eurobarometer, people in Estonia did not consider environmental pollution-related adverse health effects (66%) in 2005 (Eurobaromeeter, 2005) to be as possible as they consider them now (2024, 70%) (Eurobaromeeter, 2024). Bio-psycho-social research has demonstrated correlations between actual pollution levels, perceived pollution, perceived health risks, and health symptoms (Andersson et al., 2013; Crichton and Petrie, 2015; Orru et al., 2018). Analysis has proved that annoyance from air pollution is related to subjective health assessments as well as to respiratory symptoms, e.g., chest tightness, wheezing or cough, suggesting that annoyance might lead to health complaints as well as stress (Jacquemin et al., 2007; Machado et al., 2021; Shepherd et al., 2016; Stenlund et al., 2009). Studies show that exposure to a chemical, noise or air pollution irritates of the olfactory or sound sensors, which in turn activates the autonomic nervous system, affecting our physiology and emotions (Sucker et al., 2008). However, the relationship may also be bidirectional: symptoms could heighten individuals' sensitivity to air pollution. The risk perception of air pollution varied significantly in different parts of Estonia, being the highest in Ida-Viru County, as 10% of its residents find air pollution unbearably disturbing (the respondents had to rate on a scale of 10 how much air pollution bothers them). Nonetheless, the observation that residents of Ida-Viru, who report higher levels of annoyance might be, also experience more frequent respiratory issues compared to those in other regions, indicates that their annoyance is linked to the objective environmental conditions in the Ida-Viru region.

Regarding other mediating the relationship between air pollution and annoyance, it has been observed that women have higher odds of being annoyed by air pollution. This finding aligns with earlier research (Pilotto et al., 1999). As stated in previous studies, ethnic background, i.e., being a member of the majority group of Estonians or the minority group of Russians, income, and education do not significantly affect the odds of being annoyed. Thus, in the Ida-Viru region, socio-economic vulnerability does not significantly differentiate levels of annoyance from environmental health. Nevertheless, such disparities have previously been found in other social contexts (Fung et al., 2007; Jannus-Pruljan et al., 2004).

In addition to the direct health effects of industrial air pollution, the annoyance caused by pollutants such as benzene and the unpleasant odour of hydrogen sulphide is also a problem in Ida-Viru County. According to the WHO, people can start to smell the ('rotten egg') odour from a hydrogen sulphide concentration at very low levels, as of 11 $\mu g/m^3$ (WHO, 2003). Given the individual variability in the smell sensitivity, some people may perceive unpleasant odour even at lower concentrations. Previous studies in the area have shown that residents living at a distance of 1.0–3.5 km from the oil shale chemical and the energy complex at Kiviõli were four times more likely to complain of unpleasant odours (Этлин, 1989). This is a sleeping disorder due to unpleasant odour was 1.8 times higher, and 1.3 times higher for headaches, than people living further away (Этлин, 1989). To mitigate the specific odour emissions, shale oil plants (VKG Group and Kiviõli Oil Shale Processing and Chemicals Plant) have begun to take measures to ameliorate the situation, notably by enhancing the hermetic sealing of their various containers. Despite these achievements, the level of annoyance has remained high or even increased. This may also be attributed to the increased expectations of residents concerning environmental conditions (Wilson et al., 2008). Even though there is no systematic research in place for assessing the odour annoyance to life quality, it is documented that from 2010–to 2016, residents' of Kohtla-Järve town reported 798 times of unpleasant odours in the area (Kesanurm et al., 2016). The perception of risk and the related beliefs about pollution and its health effects may provoke annoyance. Caution towards informing the public about the health effects of environmental exposure should be considered.

7. CONCLUSIONS

1. Based on modelled annual average air pollution concentrations in Ida-Viru County, the Kohtla-Järve area is the most affected in terms of particulate matter ($PM_{2.5}$ and PM_{10}), formaldehyde and hydrocarbons (NMHC). Narva area experiences the highest levels of benzene and phenol. Kiviõli shows elevated levels of formaldehyde and hydrocarbons (NMHC), with a slight increase in phenol. Perceived health risk from air pollution significantly contributes to annoyance from air pollution. Annoyed people have higher odds of experiencing respiratory symptoms and lower levels of self-assessed health.
2. Residents of Ida-Viru County reported higher rates of four respiratory symptoms (chest tightness, wheezing, long-term cough, shortness of breath) and five studied chronic health states, including hypertension and heart disease, compared to Estonian reference populations. These self-reported health data were statistically significantly associated with $PM_{2.5}$, benzene and phenol exposure. The prevalence of adverse health effects was also higher among those who had been working in the oil shale sector.
3. The prevalence of respiratory symptoms, asthma, and high levels of fractional exhaled nitric oxide (FeNO) (as a marker of eosinophilic airway inflammation) was significantly higher for school-aged children living in an oil shale industrial area than for the reference group living in a non-industrialised area. There was a significant association between children exposed to benzene, phenol, formaldehyde and NMHC and respiratory health and airway inflammation marker exhaled NO (FeNO). Respiratory symptoms and airway inflammation among children in Ida-Viru County could, therefore, be associated with industrial pollution.
4. The age-standardised cancer incidence rates for lung cancer in males were significantly higher in an industrial area in Estonia than in Estonia overall. One of the explanations for the higher lung cancer morbidity among males in Ida-Viru County could be associated with industrial pollution (oil shale production and shale oil extraction), yet adjustments on other lung cancer risk factors would be necessary to confirm this. Moreover, in recent decades, the difference in lung cancer incidence rates has been decreasing, which could be associated with improved environmental quality in that region as one explanation. There were no significant differences between the rates of other studied cancer sites like urinary bladder, kidney and breast cancer, leukaemia, and non-Hodgkin's lymphoma between those living in the industrialised areas and Estonia overall. Prospective follow-up studies collecting exposure data at the individual level would be warranted but are not currently feasible due to the limited data available.

8. PERSPECTIVES

People's awareness and expectations of environmental quality have significantly increased over the past 10–15 years. Conscious planning of facilities and activities, ensuring they fit organically into the environment, is crucial today. Constant consideration of all types of pollution – air, noise, water, and land – is essential to safeguard public health and promote sustainable development. Air pollution, a remediable environmental trigger, can be prevented through human interventions, such as lowering air pollution levels or limiting exposure to air pollutants. The government and local governments should strengthen air quality supervision in the most polluted areas to improve the environment.

Industrial areas still have numerous landfills, often filled with environmental waste, requiring more attention and better strategies to mitigate adverse impacts on people and communities. Local residents are also affected by legacy pollution from industrial areas, leading to respiratory problems and an increase in cardiovascular diseases. Research results indicate the need for a more focused approach to the environment and the health of residents, especially those working in the industry. Therefore, comprehensive health surveys that also cover children are necessary.

There is substantial evidence that contaminated sites are often located near socioeconomically deprived communities, a phenomenon known as environmental injustice. Deprivation is directly associated with poor health, burdened by environmental, social, and health risk factors. Historical pollution has exposed residents in industrial areas to poor air quality, leading to increased respiratory and cardiovascular diseases. Addressing environmental and social inequities, such as lower education, lower-paid work, and language barriers, is crucial for fostering a more sustainable society in industrial regions. Therefore, it is vital to ensure that all communities, especially historically marginalized ones, have equal access to a clean and healthy environment. Key findings indicate that respiratory symptoms are significantly more common among non-Estonians, even after accounting for factors like smoking. In all three studied areas (Ida-Viru, Lääne-Viru, and Tartu County), the prevalence of smokers among Estonians was lower than among non-Estonians. Research on environmental health inequalities and inequities associated with contaminated sites is still in its early stages in Europe, including Estonia. More detailed studies are needed to understand and address these disparities.

Annoyance from poor environmental conditions, such as air pollution and unpleasant odours, is an increasing concern and is related to poor mental health among people living in industrial areas. Addressing these issues and prioritizing the reduction of environmental hazards can enhance mental health and overall quality of life. Living in areas with more green spaces is recommended, and indoor air purification should be enhanced.

Industrial companies must evolve in light of new collaborative strategies to combat climate change and adopt less burdensome energy sources. Their strategies, work organization, and production processes must become more environmentally friendly, community-oriented, and sustainable. The health of people and the environment must take precedence over economic wealth. There is also a strong connection between the abundance of green areas and reduced healthcare costs. Sustainable practices benefit the environment and foster social equity by ensuring all communities can access clean air and water. Industrial companies should invest in renewable energy sources and adopt circular economy principles to minimize waste.

For Ida-Viru County, a substantial portion of the wealth generated within the region must be retained locally. This approach is crucial for reducing economic disparities, promoting community development, and enhancing residents' overall quality of life. By retaining more resources locally, Ida-Viru County can make targeted investments in infrastructure, education, healthcare, and environmental sustainability–initiatives that directly impact the well-being of its population. Such investments are essential for sustainable regional development and ensuring that the economic benefits from local industries are equitably distributed among the community. The long-term improvement of public health in Ida-Viru County depends on cooperation among policymakers, local governments, businesses, scientists, healthcare providers, and the community.

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10. SUMMARY IN ESTONIAN

Keskkonnasaastatuse tervisemõjud Kirde-Eesti põlevkivitööstuse piirkonnas

Taust

Tööstuspiirkondades ja tööstuslikult saastatud aladel on sageli kõrged õhusaaste ja muu keskkonnareostuse tasemed, mis võivad põhjustada suurenenud haigestumust ja suremust. Lisaks otsesele tervisemõjule, mida põhjustab tööstuslik kokkupuude, ilmneb kaudne tervisemõju saaste ja sellest tulenevate riskide tajumise kaudu, mis võib omakorda põhjustada pidevat ärritust ja rahulolematust.

Alates 20. sajandi algusest on Ida-Viru maakond Kirde-Eestis olnud tööstuspiirkond, keskendudes peamiselt põlevkivi (orgaanikarikas settekivim) kaevandamisele ning sellest elektri ja põlevkiviõli tootmisele. Põlevkivi kasutamine oli suurim 1980ndatel, mil tootmine ulatus kuni 30 miljoni tonnini aastas. Pärast Leningradi tuumaelektrijaama käivitamist ja Nõukogude Liidu lagunemist hakkas kaevandamismaht järk-järgult vähenema, mistõttu kahanes ka elektri eksport Venemaale. Põlevkivi kaevandamine vähenes kuni 1999. aastani umbes 9,5 miljoni tonnini aastas. Alates 2019. aastast on kaevandamismaht jäänud umbes 10 miljoni tonni juurde aastas. Põlevkivitööstus andis 2017. aastal tööd 7300 inimesele ja on üks piirkonna suuremaid tööandjaid. COVID-19 pandeemia tõttu vähenes põlevkivitööstuses töötajate arv aga 5600 inimeseni.

Ida-Viru maakond on Eesti suuruselt kolmas maakond Harju ja Tartu maakonna järel. Aastal 2024 elas seal umbes 128 000 inimest ehk oluliselt vähem võrreldes 2000. aastaga, mil elanike arv oli umbes 183 000. Elanikkonna struktuur on viimastel aastatel samuti muutunud, kaldudes enam eakate poole. Viimase 20 aasta jooksul on eluiga Eestis kasvanud kiiremini kui Euroopa Liidu riikide keskmine. 2022. aastaks oli vahe Euroopa Liidu keskmisega (80,6 aastat) vähenenud ühe aastani naiste ja nelja aastani meeste puhul. Võrreldes teiste maakondadega on Ida-Viru maakonnas eluiga endiselt kõige lühem, jäädes Eesti keskmisest natuke üle kahe aasta lühemaks. Eluiga mõjutab oluliselt ka haridustase: statistikaameti andmetel elas kõrgharidusega inimene 2021. aastal Eestis 11 aastat kauem kui põhiharidusega inimene.

Enesehinnanguline hea tervis annab hea ülevaate nii haiguse või vigastuse puudumisest kui ka füüsilisest, vaimsest ja sotsiaalsest heaolust. Hea või väga hea tervise tajumine on Euroopa elanike hulgas viimase 15 aasta jooksul olnud keskmiselt 67–68%. Eestis hindas 2010. aastal oma tervist väga heaks või heaks ainult 52% inimestest, mis 2022. aastaks suurenes 58%ni. Samas tajuvad Ida-Viru maakonna elanikud oma tervist halvemini kui ülejäänud Eesti elanikud – 2022. aastal pidas oma tervist ja heaolu heaks vaid 42% sealsetest inimestest.

Tervena elada jäänud aastate arv sünnihetkel näitab, kas meie viimased eluaastad elatakse heas tervises või mitte. Keskmine tervena elada jäänud aastate arv sünnihetkel oli 2021. aastal ELis 63,6 aastat. Viimase kümne aasta jooksul on eurooplaste tervena elada jäänud aastate arv sünnihetkel kasvanud ligi kaks aastat. Samas on see Eestis jäänud ELi keskmisest seitse aastat madalamaks, olles 2021. aastal 56,7 aastat. Ida-Viru maakonnas on tervena elada jäänud aastate arv keskmiselt neli aastat madalam kui Eestis keskmiselt ja üle kümne aasta madalam kui ELis.

Kokkupuude õhusaaste ja tööstuslike saasteainetega põhjustab suurenenud haigestumust ja suremust südame-veresoonkonna ning hingamisteede haigustesse. Südame-veresoonkonna haigustesse suremus on viimase 19 aasta jooksul olnud Ida-Viru maakonnas 20% suurem kui Eestis keskmiselt. Erinevus Eesti keskmisest oli väikseim 2007. aastal (8,2% suurem) ja suurim 2016. aastal (30% suurem), seejärel on suremus vähenenud.

Lühiajaline kokkupuude õhusaastega võib aga süvendada mitmeid hingamisteede haigusi, sealhulgas astmat, bronhiiti ja kroonilist obstruktiivset kopsuhaigust (KOK). Astmasse haigestumus on Ida-Viru maakonnas olnud aastaid umbes 2% suurem kui Eestis keskmiselt.

Vähk on samuti üks tõsine haigus, mis on omakorda seotud tööstusliku saastega. Viimastel aastatel on meeste vähki haigestumus Eestis olnud suurem kui ELi keskmine, kuid naiste puhul väiksem kui ELi keskmine. Vähihaigestumus (v.a nahavähk (muud)) on alates 2010. aastast Ida-Viru maakonnas suurenenud ja sellest ajast alates püsinud 15% suurem kui Eesti keskmine. Teisalt on vähki suremus Ida-Virumaal jäänud aastaid samaks, olles sarnane Eesti keskmisega või veidi väiksem, ent hakanud hiljuti suurenema.

Ühiskonna ootused keskkonnakvaliteedi suhtes on viimase aastakümne jooksul märkimisväärselt suurenenud. Tänapäeva ühiskonnas on äärmiselt oluline, et erinevad loodavad struktuurid ja tegevused oleksid hoolikalt ja teadlikult integreeritud looduslikku keskkonda. Seetõttu on tõhus saastekäsitlus – sealhulgas õhu-, müra- ja veesaaste ning pinnasereostuse vähendamine – äärmiselt oluline. Tööstuslikult saastatud alad on olnud pikki aastaid koormavad nii keskkonnale kui ka inimeste tervisele ja heaolule.

Eesmärgid

Uurimistöö eesmärk oli hinnata põlevkivi kaevandamise ja kasutamisega seotud tervisemõju Ida-Virumaal elavate inimeste hulgas.
Alaeesmärgid olid:

1. Selgitada välja õhukvaliteedi olukord Ida-Viru maakonnas ja inimeste häiritus õhusaaste tõttu.
2. Uurida seoseid tööstuslike saasteainete ja täiskasvanud elanike terviseseisundi vahel.
3. Tuvastada, kas põlevkivitööstuse piirkonnas elavate laste hingamisteede probleemide esinemissagedus on jätkuvalt suurem kui mujal Eestis ja seotud põlevkivitööstusest pärineva saastega.
4. Analüüsida Eesti põlevkivitööstuse piirkonnas vähktõve esinemissageduse ajalisi trende ja võrrelda neid üleriigiliste haigestumusmääradega.

Metoodika

Põlevkivisektori tervisemõju uuringu raames teostati kolm eraldiseisvat uuringut:

1. **Täiskasvanute läbilõikeline uuring Ida-Virumaal ning kontrollpiirkondades Lääne-Virumaal ja Tartumaal.** Juhuvalimi teel saadeti uuringuküsimustik Ida-Virumaal 2097 isikule vanuses 18–70 aastat, Lääne-Virumaal 403 inimesele samas vanuses ning Tartumaal 2750 inimesele vanuses 18–40 aastat. Kontrollgruppi lisandusid uuritavad eelnevast RHINE III uuringust Tartus, kus vastanuid oli 1370. Küsimustik sisaldas erinevaid hingamisteede tervisega seotud küsimusi, nagu vilistav hingamine, pikaajaline köha ja astma ning kõrgvererõhktõbi, insult ja muud südame-veresoonkonnahaigused.
2. **Laste läbilõikeline uuring Ida- ja Lääne-Virumaa 8–12-aastaste õpilaste hulgas.** Sellele uuringule lisati Tartumaa samavanuste laste andmed SINPHONIE (Schools Indoor Pollution and Health Observatory Network in Europe) uuringust. Uuringu valim koosnes 1326 juhuslikult valitud 3.–4. klassi õpilasest. Koolid valiti juhuslikkuse alusel, arvestades sotsiaaldemograafilist olukorda ning tööstusliku saaste taset. Küsimustik sisaldas erinevaid hingamisteede sümptomitega seotud küsimusi, nagu vilistav hingamine, öine köha, kuiv köha, aevastamine, tilkuv nina, rögaeritus ja astma. Lisaks viidi koolides läbi kopsufunktsiooni objektiivseks hindamiseks spiromeetria ning mõõdeti fraktsioneeritud lämmastikoksiidi (FeNO) sisaldust väljahingatavas õhus.
3. **Registripõhine ökoloogiline uuring.** Põlevkivisektori piirkonnas elamise esmase kantserogeense mõju hindamiseks kasutati Eesti vähiregistri vähihaigestumuse andmeid perioodist 1992–2015. Uuringu vähkkasvajate paikmete valim koostati eelnevalt teadusuuringutes kinnitust leidnud erinevate vähijuhtude esinemissageduse alusel põlevkivi, nafta töötlemise ja muu keemiatööstuse sektoris. Vähipaikmete valikul registrist kasutati RHK-10 koode. Uuritavateks vähipaikmeteks olid kopsuvähk (C34), neeruvähk (C64), mitte-Hodgkini tüüpi lümfoom (C82–C85), kusepõievähk (C67), leukeemia (C93–C95) ja rinnavähk (C50). Uuringu käigus võrreldi Eesti keskmisi vähihaigestumuskordajaid põlevkivitööstusega seotud omavalitsusüksustes (Ida-Viru maakonna põhja- ja idaosa) ning põlevkivitööstusega mitteseotud kohalikes omavalitsustes (Ida-Viru maakonna lõunaosa) erinevate vähipaikmete lõikes.

Välisõhu kvaliteedi hindamiseks ja õhusaaste leviku modelleerimiseks kasutati 2001.–2013. aasta Ida-Virumaa saasteainete heitkoguseid. Modelleerimine viidi läbi, kasutades Eesti õhukvaliteedi juhtimissüsteemi ning selles sisalduvat tarkvara Airviro. Mudeli sisenditeks olid keskkonnaagentuuri koostatud välisõhusaasteallikate andmebaas OSIS2013, liiklusandmebaas traffic2007, kohtkütte andmebaas ning 2013.–2014. aasta meteoandmed Aseri meteomastist. Hajuvusarvutused teostas Eesti keskkonnauuringute keskus kõikide teadaolevate Ida- ja Lääne-Virumaal asuvate välisõhu saasteallikate ning eraldi ainult põlevkivisektoriga seotud käitiste kohta. Modelleeriti aasta keskmised fenooli, benseeni, formaldehüüdi, mittemetaansete süsivesinike, peenosakeste (PM_{10}) ja eriti peente osakeste ($PM_{2,5}$) sisaldused, mis omakorda geokodeeriti iga inimese koduse aadressi alusel.

Vähiregistripõhises uuringus loeti Kohtla-Järve (Järve linnaosa), Kiviõli ja Püssi suure eksponeeritusega aladeks ehk nn keemiatööstuse piirkonnaks. Kui sinna lisati Narva linn, kujunes sellest nn keemiatööstuse ja elektrijaamade piirkond.

Kolme maakonna erinevuste hindamiseks kasutati hii-ruut testi. Lisaks võrreldi piirkondade soolisi, rahvuslikke ja muid erinevusi. Regressioonimudelit kohandati võimalike segavate tegurite suhtes, nagu sugu, vanus, kehamassiindeks, tubakasuits ja perekonna sissetulek ühe inimese kohta. Statistiliselt oluliseks loeti tulemused $p < 0,05$ korral. Andmeanalüüs viidi läbi programmidega Stata ja MS Excel. Uuringu protokolli kinnitas Tartu Ülikooli inimuuringute eetikakomitee.

Tulemused

Ida-Viru maakonna modelleeritud aastakeskmiste õhusaaste kontsentratsioonide põhjal olid kõrgeimad $PM_{2,5}$ ja PM_{10} tasemed Kohtla-Järve piirkonnas, kõrgeimad benseenitasemed Narva piirkonnas ning vähesel määral ka Kohtla-Järve piirkonnas. Kõrgeimad fenoolitasemed ilmnesid Narva piirkonnas ning väiksemal määral Kiviõli piirkonnas. Kõrgeimad formaldehüüdi tasemed registreeriti Jõhvi, Sillamäe ja Narva piirkonnas ning kõrgeimad alifaatsete süsivesinike (NMHC) tasemed registreeriti Kohtla-Järve ja Kiviõli piirkonnas.

Idavirumaalased olid statistiliselt enim häiritud ka õhusaastatusest. Õhusaastatus häiris enim neid inimesi, kellel esines raskustunnet rinnus, külmetuseta vilistavat hingamist, köhimishooge (Ida-Virumaa); õhupuudust ja pikaajalist köha (Tartumaa). Inimesed, kellel esinesid vereringeelundite haigused, õhusaastatust häirivaks ei pidanud.

Aastatel 2014–2015 oli viimase 12 kuu jooksul 42% Ida-Virumaa täiskasvanud elanikest esinenud külmetuseta vilistavat hingamist ning kolmandik tundnud raskustunnet rinnus. Tartumaal esines neid sümptomeid pea poole vähematel inimestel kui Ida-Virumaal. Pikaajalist köha esines 29% Ida-Virumaa elanikest, samas kui tartumaalaste ja läänevirumaalaste seas oli vastav näitaja keskmiselt 21%. Kõrgvererõhktõbe raporteeris 34% Ida-Virumaa inimestest; Tartumaal esines see 16% elanikest.

Ida-Viru maakonna elanikud raporteerisid statistiliselt oluliselt enam vilistavat hingamist, raskustunnet rinnus, õhupuudust, köhimishooge ja astmahooge. Samuti oli neil varasemalt esinenud oluliselt enam vilistavat hingamist, pikaajalist köha, kõrgvererõhktõbe, südamehaigusi, südameinfarkti, insulti ja diabeeti. Kõiki nimetatud tervisenähte esines statistiliselt oluliselt enam mitte-eestlaste hulgas. Vilistavat hingamist, raskustunnet rinnus, kõrgvererõhktõbe, südamehaigusi, südameinfarkti, insulti ja diabeeti esines statistiliselt enam inimeste hulgas, kes töötasid või olid varem töötanud põlevkivisektoris.

Doktoritöö tulemustest selgus, et Ida-Virumaa inimestel, kes on enam eksponeeritud benseenile, on 1,98 (95% CI 1,11–3,53) korda suurem šanss haigestuda infarkti. Inimestel, kes puutuvad enam kokku fenooliga, on vastavalt 1,44 (1,03–2,00), 1,48 (1,06–2,07) ja 2,17 (1,23–3,83) korda suurem šanss tunda raskustunnet rinnus, olnud kunagi pikaajaline köha ja oht haigestuda infarkti. Inimesed, kes puutuvad enam kokku eriti peente osakestega ($PM_{2,5}$), on vastavalt 1,13 (1,02–1,26), 1,16 (1,03–1,31) ja 1,22 (1,04–1,42) korda suurem šanss kogeda raskustunnet rinnus, õhupuudust ja astmahoogude esinemist.

Ida-Viru maakonna koolilaste seas oli eneseraporteeritud astma levimus 13%, Lääne-Virumaal 10% ja Tartumaal 7%. Vilistavat hingamist esines 21% Ida-Virumaa lastest ja 10% Tartumaa lastest. Külmetuseta öist köha esines 24% Ida-Virumaa koolilastest, 16% Lääne-Virumaa ja 6% Tartumaa lastest. Igal kümnendal Ida-Virumaa koolilapsel oli kõrgenenud väljahingatava lämmastikoksiidi (FeNO ≥ 30 ppb) tase, kuid neil puudus astma diagnoos; teistes maakondades oli see näitaja keskmiselt 4,5%. Ida-Viru maakonnas esines statistiliselt oluliselt enam vilistavat hingamist, külmetuseta nohu, rögaeritust ning arsti diagnoositud astmat. Viimase 12 kuu jooksul esines Ida-Virumaa laste hulgas enam külmetuseta vilistavat hingamist ja öist kuiva köha.

Statistilisel analüüsil ilmnes, et lastel, kes elavad keemiatööstuse ja elektrijaamade piirkonnas, oli 1,63 (1,03–2,60) korda suurem šanss, et nende väljahingatava õhu NO-tase ületas 30 ppb, ent neil puudus astma diagnoos. Ida-Viru maakonna kooliõpilastel, kes olid enam eksponeeritud benseenile, oli vastavalt 1,03 (1,01–1,06), 1,05 (1,01–1,10), 1,04 (1,01–1,07), 1,05 (1,01–1,10), 1,06 (1,01–1,11), 1,05 (1,01–1,09) ja 1,05 (1,00–1,10) korda suurem šanss, et neil on kunagi olnud külmetuseta nohu, astmahood, viimase 12 kuu jooksul esinenud külmetuseta öist köha, mõnel päeval aastas kuiva köha, rögaeritust, FeNO > 30 ppb või FeNO > 30 ppb, ent puudub astma diagnoos.

Lastel, kes puutusid enam kokku formaldehüüdiga, oli vastavalt 1,13 (1,02–1,27), 1,17 (1,00–1,36), 1,21 (1,04–1,42), 1,14 (1,01–1,27), 1,23 (1,06–1,45), 1,22 (1,06–1,41) ja 1,26 (1,06–1,50) korda suurem šanss, et neil on kunagi olnud külmetuseta nohu, astma diagnoos, astmahood, viimase 12 kuu jooksul olnud külmetuseta öist nohu, mõnel päeval aastas kuiva köha, rögaeritust, FeNO ≥ 30 ppb või FeNO ≥ 30 ppb, ent puudub astma diagnoos. Fenooliga kokku puutuvatel Ida-Virumaa lastel oli 1,01 (1,00–1,01) korda suurem šanss, et neil on FeNO ≥ 30 ppb või FeNO ≥ 30 ppb, ent puudub astma diagnoos. Ida-Viru maakonna kooliõpilased, kes elavad kõrgemate NMHC tasemete piirkonnas, oli vastavalt 1,75 (1,17–2,62) ja 1,04 (1,01–1,07) korda suurem šanss, et nende väljahingatava õhu FeNO ≥ 30 ppb või FeNO ≥ 30 ppb, ent puudub astma diagnoos.

Kokku diagnoositi aastatel 1992–2015 Ida-Virumaal valitud paikmetesse 6752 vähi esmasjuhtu, millest enamuse moodustasid kopsuvähk (41%). Eestis haigestuti valitud paikmetesse keskmiselt 65-aastaselt, seevastu Ida-Virumaal 63-aastaselt. Uuritud vähipaikmetest haigestusid Ida-Virumaa mehed enim kopsuvähki, samuti neeru- ja kusepõievähki. Leukeemiat ja mitte-Hodgkini lümfoome esines meeste ja naiste hulgas võrdselt.

Uuritud perioodil (1992–2015) oli kopsuvähi esinemissagedus Eesti keskmisest kõrgem põlevkivitööstusega seotud omavalitsusüksustes elavate meeste hulgas. Perioodi alguses rohkem (~130 juhtu 100 000 elaniku kohta) ja lõpus vähem (~120 juhtu 100 000 elaniku kohta). Kopsuvähi haigestumuskordaja oli tunduvalt kõrgem ka põlevkivitööstusega otseselt mitte seotud piirkonnas elavate meeste hulgas.

Perioodi esimesel poolel oli põlevkivitööstusega seotud omavalitsusüksustes elavatel inimestel Eesti keskmisest kõrgem neeru- ja kusepõievähi haigestumus, samuti kusepõievähi haigestumuskordaja meeste hulgas. Perioodi teises pooles oli põlevkivitööstusega seotud meeste hulgas Eesti keskmisest kõrgem mitte-Hodgkini lümfoomi haigestumuskordaja.

Samal perioodil oli põlevkivitööstusega seotud omavalitsusüksustes elavate naiste hulgas Eesti keskmisest kõrgem kopsu- ja neeruvähi haigestumuskordaja. Perioodi teises pooles olid kõikide vaadeldud paikmete haigestumuskordajad Ida-Virumaa naiste hulgas Eesti keskmisest madalamad.

Kokkuvõte

Modelleeritud aastakeskmiste õhusaasteainete sisalduse alusel oli Ida-Viru maakonnas kõige enam saastatud piirkond Kohtla-Järve, kus tuvastati kõrgeimad $PM_{2,5}$, PM_{10}, formaldehüüdi ja alifaatsete süsivesinike (NMHC) tasemed. Narva piirkonnas oli kõrgeim benseeni- ja fenoolisisaldus. Kiviõlis oli kõrgenenud formaldehüüdi ja NMHC tase, samuti oli suurenenud fenoolisisaldus. Doktoritööst ilmnes, et Ida-Viru maakonna elanikud olid õhusaaste tõttu enam häiritud ning hindasid oma terviseseisundit kehvemaks võrreldes teiste Eesti piirkondade elanikega.

Ida-Virumaa täiskasvanud elanikud raporteerisid sagedamini hingamisteede haigusnähtudest (raskustunne rinnus, vilistav hingamine, pikaajaline köha, õhupuudus) ja mitmetest teistest kroonilistest haigustest, sealhulgas kõrgvererõhktõvest ja südamehaigustest, kui Lääne-Virumaa ja Tartumaa elanikud. Mitmed neist haigusnähtudest olid statistiliselt oluliselt seotud $PM_{2,5}$, benseeni ja fenooli kokkupuutega. Tervisekaebuste ja haiguste levimus oli suurem põlevkivisektoris töötanud inimeste hulgas, samuti ilmnesid olulised rahvustevahelised erinevused – mitte-eestlastel esines enamikku vaadeldud tervisekaebusi ja kroonilisi haigusi sagedamini.

Põlevkivitööstuse piirkonnas elavatel kooliõpilastel oli hingamisteede sümptomite, astma ja suurenenud FeNO taseme levimus märgatavalt kõrgem kui tööstusest eemal elavatel lastel. Benseeni, fenooli, formaldehüüdi ja NMHCga kokku puutunud lastel oli statistiliselt oluline seos hingamisteede tervise ja põletikega. Seega võivad Ida-Virumaa laste hingamisteede sümptomid ja põletikud olla seotud tööstussaastega.

Vanuse järgi standardiseeritud kopsuvähi esinemissagedus oli tööstuspiirkonnas elavatel meestel oluliselt kõrgem kui Eestis keskmiselt. Viimastel aastakümnetel on see erinevus siiski märgatavalt vähenenud, mida võib ühelt poolt seostada keskkonnakvaliteedi paranemisega selles piirkonnas ning teiselt poolt suitsetamise vähenemisega. Teiste uuritud vähipaikmete, nagu kusepõie-, neeru- ja rinnavähk, leukeemia ja mitte-Hodgkini lümfoom, esinemissageduses ei ilmnenud olulisi erinevusi tööstuspiirkonna ja Eesti keskmise vahel.

Järeldused ja soovitused

Inimeste teadlikkus ja ootused keskkonna kvaliteedi teemal on viimase paari aastakümne jooksul märkimisväärselt kasvanud. Kõigi peamiste saastekandjate – õhu, müra, vee ja pinnase – kvaliteedi pidev jälgimine ja arvesse võtmine on rahvatervise kaitseks ja kestliku arengu edendamiseks hädavajalik. Õhusaaste on välditav keskkonnategur, mistõttu on äärmiselt oluline, et riik ja kohalikud omavalitsused tugevdaksid õhukvaliteedi järelevalvet ja paigaldaksid täiendavaid seirejaamu kõige saastatumatesse piirkondadesse, et saada parem ülevaade keskkonnaseisundist.

Kohalikke elanikke mõjutab ka tööstuspiirkondade pärandreostus, millega pikaajaline kokkupuude võib olla praegu avalduvate hingamisteede probleemide ja südame-veresoonkonna haiguste põhjuseks. Seetõttu on vaja terviklikke terviseuuringuid, mis hõlmavad nii lapsi, täiskasvanuid kui ka vanemaealisi.

Saastunud alad asuvad sageli sotsiaalmajanduslikult ebasoodsas olukorras olevate kogukondade lähedal, mida võib omakorda nimetada keskkonnaalaseks ebavõrdsuseks. Keskkonna ja sotsiaalsete ebavõrdsuste, nagu madalam haridustase, madalamalt tasustatud töö ja keelebarjäärid, lahendamine on aga väga vajalik, et tööstuspiirkondades oleks üldse võimalik edendada säilenõtkemat ühiskonda. Sotsiaalsete probleemide lahendamise üks eeldusi on, et kõikidel kogukondadel, eriti ajalooliselt marginaliseeritutel, oleks võrdne juurdepääs puhtale ja tervislikule elukeskkonnale. Keskkonnaalase ebavõrdsuse paremaks mõistmiseks ja selle vähendamiseks, eriti saastunud piirkondades, on vajalikud üksikasjalikumad uuringud.

Lisaks saastunud õhule on tööstuspiirkondade inimesed keskmiselt enam rahulolematud ka tööstusest tulenevate lõhnahäiringute tõttu. Pidev rahulolematus halva elukeskkonnaga võib lisaks krooniliste haiguste avaldumisele halvendada elanike vaimset tervist. Seetõttu tuleb vähendada erinevat tüüpi keskkonnaohte ja luua täisväärtuslik elukeskkond, mis parandaks nii kohalike elanike tervist kui ka üldist elukvaliteeti.

Radoonitundlikes piirkondades, nagu Ida-Virumaa, on oluline teadvustada radooniga (maitsetu ja lõhnatu radioaktiivne gaas) kokkupuutest tulenevaid terviseriske, kuna see on mittesuitsetajate hulgas peamine kopsuvähi põhjus. Rahvatervise riske aitab maandada elanike suurem teadlikkus radooniga seotud terviseriskidest ja leevendusmeetmete rakendamine.

Ida-Viru maakonna ja selle elanike jaoks on oluline, et märkimisväärne osa piirkonnas loodud rikkusest jääks kohapeale. Piisavate ressursside olemasolul on võimalik leevendada majanduslikku ebavõrdsust, edendada kogukonna arengut ning parandada elanike üldist elukvaliteeti hariduse, tervishoiu ja puhtama keskkonna kaudu. Ida-Virumaa inimeste pikaajalise tervise ja heaolu paranemine sõltub otseselt poliitikakujundajate, kohalike omavalitsuste, ettevõtete, teadlaste, tervishoiusüsteemi ja kogukonna koostööst.

Uute strateegiate, nagu õiglane üleminek, valguses on tähtis võtta kasutusele keskkonnasõbralikumad tehnoloogiad, et seeläbi leevendada kliimamuutuste mõju ja vähendada sotsiaalset ebavõrdsust. Ettevõtete töökorraldus ja tootmisprotsessid peavad muutuma keskkonnasõbralikumaks (nt rakendades ringmajanduse põhimõtteid), kogukonnale orienteeritumaks ja kestlikumaks. Inimeste ja keskkonna tervis peab olema majanduslikest huvidest alati eespool. Jätkusuutlikud tavad toovad kasu keskkonnale ja edendavad sotsiaalset õiglust, tagades, et kõigil kogukondadel oleks juurdepääs puhtale õhule ja veele. Seades igas valdkonnas prioriteediks kestlikkuse, loome aluse tervemale ja vastupidavamale ühiskonnale.

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PUBLICATIONS

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