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Faculteit Bedrijfseconomische Wetenschappen

master handelsingenieur

Masterthesis

Environmental impacts of COVID-19 pandemic measures on companies: A systematic review of empirical studies

Lore Box

Scriptie ingediend tot het behalen van de graad van master handelsingenieur, afstudeerrichting operationeel management en logistiek

PROMOTOR :

Prof. dr. Stephan BRUNS

BEGELEIDER :

De heer Teshome Kebede DERESSA

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Preface

In front of you is my thesis on the environmental impact of COVID-19 measures. With this thesis, I conclude my master's degree in business engineering operational management and logistics at Hasselt University.

I had the honour of writing my master's thesis on an environment-inspired topic. The environmental aspect of my thesis is the main reason why I wanted to write about this topic. I am quite interested in the impact of people and companies on the environment. My bachelor thesis was also on an environmental theme. During the COVID-19 pandemic, businesses had to close down and human activities were restricted. So this thesis gave me an opportunity to delve into the impact of people and businesses on the environment.

The content of my thesis is mainly intended for people who are interested in these kinds of topics, but also for people who are concerned about the current environmental crisis we are facing. Furthermore, I think my thesis can also be an inspiration for governments trying to develop an action plan to combat the environmental crisis.

Overall, writing my thesis went pretty smoothly. However, there were some things that made writing more difficult. First, to write my thesis, I conducted a systematic review. This was something new for me and it took some time to get used to this new method of conducting a literature review. Secondly, it was sometimes difficult to reduce all the papers written on COVID-19 to a number of papers I could handle, because apparently many people were eager to write about COVID-19. And finally, this was also the first time I wrote such a large text in a language other than my mother tongue.

I would like to thank my promoter, Stephan Bruns, and my supervisor, Teshome Deressa, not only for giving me the opportunity to write on this topic, but also for their feedback and guidance. And finally, I would also like to thank my mother for giving me the opportunity to study.

Abstract

The SARS-CoV-2 virus caused millions of deaths and even more infections. To prevent the spread of the virus, governments around the world began to restrict all aspects of life. Currently, it seems that the spread of COVID-19 virus is under control, so this is the ideal time to look back and evaluate the COVID-19 period and whether the COVID-19 measures led to environmental improvement. This thesis will answer the following two questions, "What COVID-19 measures were imposed (on companies) to get the global lockdown operational?" and "What impact did the measures have on the environment?" The answer to these questions gives us some insight into the role that companies and humans play in the environmental changes we are currently facing. Moreover, the COVID-19 pandemic gives us a unique opportunity to start with a clean slate and reconsider or develop action plans to combat the current climate crisis.

To answer both questions, a systematic review was conducted with 108 papers. The ROSES guidelines were followed to conduct the systematic review. Four databases were used to collect the 108 papers, namely Web of Science, UHasselt library, PubMed and Google Scholar. The systematic review includes papers from around the world, written in English and published in 2020, 2021 or 2022.

Many non-essential businesses had to close their doors during the worst stages of the pandemic, and even if they were allowed to reopen or remain open, strict rules such as wearing masks and keeping their distance had to be followed. To answer the first research question, "What COVID-19 measures were imposed (on companies) to get the global lockdown operational?", the following non-pharmaceutical measures and their effectiveness are discussed: personal protective equipment (PPE), hygiene measures, travel restrictions, closures, contact tracing, staying at home, isolation and quarantine. Overall, we can conclude that all measures discussed were indeed effective in limiting the spread of COVID-19. However, they are most effective when combined with other restrictions. For example, contact tracing is only really effective when combined with quarantine, isolation and/or travel bans. It should also be noted that some measures, such as contact tracing and travel bans, need to be applied widely and for an extended period of time at an early stage. Furthermore, some measures, such as travel restrictions and a stay-at-home policy, are considered to be very effective but result in quite significant economic harm. A stay-at-home policy causes people to work at home, but in some cases people such as waiters cannot work at home. Therefore, most countries try to avoid long-term stay-at-home policies. On a country-by-country basis, we see that all countries handled the pandemic in different but similar ways. Some countries like China and South Africa and Uganda had quite strict restrictions. While other countries such as Sweden and Tanzania had less strict restrictions.

All these measures implemented by governments had environmental impacts. My thesis studies the impact of the COVID-19 restrictions on waste, water, noise and air quality. To reach a conclusion on air quality, the concentrations of the following elements were studied: sulphur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter ($PM_{2.5}$ & PM_{10}), carbon monoxide (CO), carbon dioxide (CO_2) and ozone (O_3) for each continent. Global reductions in NO_2, $PM_{2.5}$, PM_{10}, SO_2, CO and CO_2 were recorded due to reduced traffic and economic and industrial activities. However, an increase in SO_2 emissions

was observed in some parts of India, such as South India and Mumbai. No changes in SO_2 levels were recorded in the industrial areas of Malaysia because power plants had to remain operational during the lockdown. Furthermore, NO_2 pollution decreased all over the world. The transportation sector is one of the major sources of NO_2 pollution. During the lockdown, traffic decreased dramatically, leading to a significant reduction in NO_2 emissions. The greatest reduction in NO_2 emissions was measured mainly in larger cities. In some parts of India, however, NO_2 levels were elevated due to fires.

Ozone is the only pollutant that increased in most parts of the world. The increase in ozone is probably caused by reductions in NO_x concentrations. In some parts of the world, however, ozone levels have decreased or remained the same. This is the case in certain cities in Spain, India, Egypt and Indonesia, among others. On the other hand, $PM_{2.5}$ and PM_{10} and CO and CO_2 concentrations decreased during the lockdown period. However, the decrease in NO_2 concentrations was greater than the decrease in $PM_{2.5}$ and PM_{10} emissions in most parts of the world. This is because traffic emissions, which decreased significantly during the shutdown, are a major source of NO_2 emissions but only a minor source of PM emissions. It is also important to note that the reductions in air pollution were only temporary. Finally, some changes in emissions are partly caused by meteorological factors. Thus, when studying the changes in pollutants during the lockdown, it is very important to consider meteorological data as well.

The COVID-19 restrictions also caused a change not only in the amount of waste, but also in its management. Our amount of household food waste decreased during the COVID-19 period due to more home cooking, use of leftovers, less frequent trips to the supermarket and meal planning. On the other hand, the use of personal protective equipment, such as masks, gloves and decontamination wipes, caused a huge increase in plastic waste. And unfortunately, not all plastic waste was handled properly, so parts ended up in the environment and caused the release of toxic chemicals into the environment and the consumption of microplastics by fish. Moreover, the COVID-19 pandemic also led to an increase in online shopping, which increased packaging material. Finally, medical waste increased dramatically as well.

Because of the increase in plastic and contaminated waste, existing waste management systems had to make some adjustments to cope with all the waste, but also to protect the environment and people. Waste collectors were required to wear personal protective equipment to prevent contamination. Moreover, waste was often stored for a certain time until it was COVID-19 free or other alternative technologies, such as autoclaves and pyrolysis, were used to sterilise or dispose of the waste. In China, they even built a new incinerator and emergency storage facilities to handle the increasing amount of waste. The COVID-19 pandemic also caused people to start using plastic bags again, which may have rekindled the throw away culture.

The COVID-19 restrictions had a number of positive and negative impacts on water quality. COVID-19 increased the clarity of water sources around the world. Moreover, researchers discovered an improvement in water quality during the lockdown, leading to more fish and less underwater noise. Beaches also benefited from the lack of tourism. On the other hand, wastewater quality deteriorated. The use of disinfectants and antibiotics increased the organic load of wastewater. The COVID-19 pandemic also caused an increase of plastic in the water, which will have long-term negative effects on humans and marine organisms. Finally, the restrictions of COVID-19 led to a reduction in noise, which was mainly due to the reduction in traffic. However, it should be noted that the reduction in noise is only temporary.

The content of my thesis is based on 108 papers, so it provides a nice overview of the research that has been done regarding COVID-19 and the environment. However, there are still some limitations. I only included non-pharmaceutical measures. In addition, my systematic review contained only a limited number of articles on the continent of Oceania. Furthermore, my thesis only consists of English-language articles from the years 2020, 2021 and 2022. Finally, I looked at the effect of restrictions on air quality. But for future research, it would also be interesting to look at the opposite question, "Did poor air quality cause more spread of COVID-19 virus and thus more deaths?" Despite these limitations, I still believe that my thesis can be an inspiration to combat the current climate crisis. Structural changes are needed to improve the environment in the long run, and COVID-19 gives us a chance to start over and create an action plan for a lower-emission economy.

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Introduction

COVID-19 has rocked our world. It started as a common harmless cold, but it soon became clear that COVID-19 was not so harmless. Subsequently, COVID-19 was declared a global pandemic and various measures were taken to reduce the number of deaths. Measures ranged from simply washing hands to keeping your distance and wearing a mouth mask to eventually closing national borders and shutting down countries.

Meanwhile, it has been more than three years since COVID-19 was first identified in Wuhan, China. In these three years, COVID-19 has been able to do a lot of damage (Archived: WHO Timeline - COVID-19, 2020). For instance, since the beginning of the COVID-19 outbreak until June 2023, about 767,364,883 people worldwide have been infected with COVID-19 and about 6,938,353 people worldwide have died (*WHO Coronavirus (COVID-19) Dashboard*, n.d.). COVID-19 also had a huge impact on the economy by shutting down many businesses and closing the borders (Xu et al., 2021). During the lockdown, only essential businesses were allowed to remain open and travel was made impossible (Malpede & Percoco, 2021; Donzelli et al., 2021). Working from home was encouraged as much as possible, and businesses that were allowed to remain open adhered to strict rules, such as disinfecting hands, wearing face masks and keeping their distance.

At the moment, we have COVID-19 somewhat under control and although the number of COVID-19 cases is currently on the rise and local lockdowns are back in force in China (Renders, 2022), perhaps we can take a breath and see if COVID-19 has not also had a positive impact on our world. And more specifically, what impact COVID-19 and its measures imposed on companies have had on our environment. My thesis explores this topic further.

Objectives/ relevance

Many studies have been conducted on COVID-19 and the environment, but there are not so many systematic reviews yet in which not only COVID-19 and the environment, but also companies play an important role. If we know what measures have had a positive impact on the environment, we may be able to learn from them to combat the current climate crisis. Moreover, it can also be a good indicator to see what impact companies have on the environment, as companies had to close during the corona crisis. And perhaps my thesis can teach us important lessons if we ever face a new pandemic.

My thesis examines the effect of the COVID-19 measures (imposed on companies) on the environment. The ultimate goal is to get an overview of which measures had a positive impact and which measures were very detrimental to the environment. As mentioned, important lessons for the future can be drawn from such an overview.

Research questions

My first sub-question goes as follows: "What COVID-19 measures were imposed (on companies) to get the global lockdown operational?". To answer this question, I examined all the measures imposed (on companies) to get the global lockdown operational. The government required non-essential businesses to close during the lockdown. Strict rules applied to businesses that were allowed to remain open. In the section on my first research question, I give an overview of the measures that were imposed on businesses and whether those measures varied from country to country. I also look at the effectiveness of the measures.

After answering the first sub-question, my thesis addresses the following question: "How did these measures influence the environment: *comparison before COVID-19, during COVID-19 lockdown, after the lockdown?".* In this part of my thesis, I examined the environmental effects of the measures. My thesis answers all the questions below. Did the air quality improve because there was less transport and travel became impossible, businesses had to close and global trade declined? And if air quality improved was that a long-term effect or is air pollution as bad or worse than before COVID-19? Was there more waste because we had to wear masks, use gloves and alcohol gel? How was the disposal of contaminated waste handled? Did COVID-19 affect water? And finally, did the lockdown have a positive effect on noise pollution?

From these two questions, my main research question arises, which goes as follows*: "How did the COVID-19 measures imposed (on companies) influence the global environment?"*. This question is very relevant for several reasons. COVID-19 has been plaguing our lives for more than 2 years and although the impact of COVID-19 on our lives is slightly less at the moment, the disease has claimed many lives and COVID-19 will become a disease like the flu that we will have to live with permanently. So the disease remains a hot topic today. But it may not be all doom and gloom, perhaps COVID-19 has also brought positive things and more specifically positive things for our environment. Should this be the case, we can draw some interesting lessons for the future.

Method

The best way to answer the above questions is through some kind of literature review. Specifically, I conducted a systematic review. I answered my research question and subsidiary questions by identifying, reviewing and summarising studies in this area. Different types of guidelines have been developed for systematic reviews, allowing one to assess quality. For example, you have PRISMA (Moher et al., 2009) and ROSES (Reporting standards for systematic evidence syntheses) (Haddaway et al., 2018). PRISMA was developed primarily for systematic reviews in healthcare and ROSES is developed for reviews in conservation and environmental management. Since my thesis is related to the latter area, I used ROSES. ROSES helped me include the right info in my thesis.

Literature search strategy

The databases I used to write my thesis are Web of Science, UHasselt library, PubMed and Google Scholar. To conduct my research, I used the following search terms: coronavirus, COVID-19, Sars-Cov-2, environment, pollution, climate, weather, waste, measures, lockdown, actions, borders, companies, firms, business. More specifically, I used the following search term: ((((COVID-19) OR (coronavirus) OR (Sars-Cov-2)) AND ((environment) OR (pollution) OR (climate) OR (weather) OR (waste))) OR (((COVID-19) OR (coronavirus) OR (Sars-Cov-2)) AND ((measures) OR (lockdown) OR (actions) OR (borders)) OR ((companies) OR (firms) OR (business)))) NOT (vaccine). In PubMed, this search term yielded 10,916 studies and in Google Scholar 350 studies. Both searches were conducted on 12 November 2022. On 17 January 2023, I did a search on Web of Science and it retrieved 6844 papers. After removing duplicates, only 16949 studies remained. Once title screening, abstract screening and full text screening were completed, 108 papers remained and these 108 papers were included in my systematic review. I collected 27 papers for the first research question and 81 papers for the second.

Endnote is the tool I used to complete the ROSES flowchart. With Endnote I can not only create my own personal library of papers that I have used for my systematic review, but also very easily remove papers that I have duplicates of and display my references in APA-style.

Inclusion and exclusion criteria

I only included English-language and published papers in my thesis. The papers must have been published in 2020, 2021 or 2022. I chose this period because the global corona outbreak did not really start until 2020. Furthermore, mainly the following types of studies were included in my thesis: systematic reviews, observational studies, case studies, evaluation studies, meta-analyses and randomized controlled trials. In addition, I used studies from around the world because the corona crisis was a global crisis. It is also very important to me that the articles are of good quality, so articles from low-quality journals were not cited in my thesis. The website "Scimago Journal & Country (SJR) rank" helped me to check if the papers are of good quality (*Scimago Journal & Country Rank*, n.d.). The SJR website ranks journals according to colour codes that range from green, meaning good quality, to red, meaning poor quality. My thesis contains mainly journals with a green or yellow colour. Journals with a red colour were excluded.

Data extraction and coding

The information I extracted from the papers is an overview of most of the measures taken during the corona period. I have also studied the effectiveness of the various measures. I focused mainly on the measures taken when there was no vaccine. Once I had this, I collected data on the environmental impact of these measures. For example, I looked at the concentration of certain pollutants before the lockdown and during the lockdown. Finally, I also collected information about the current situation (after the lockdown) to see if there were long-term effects on the environment or if it was all short-lived.

ROSES Flowchart

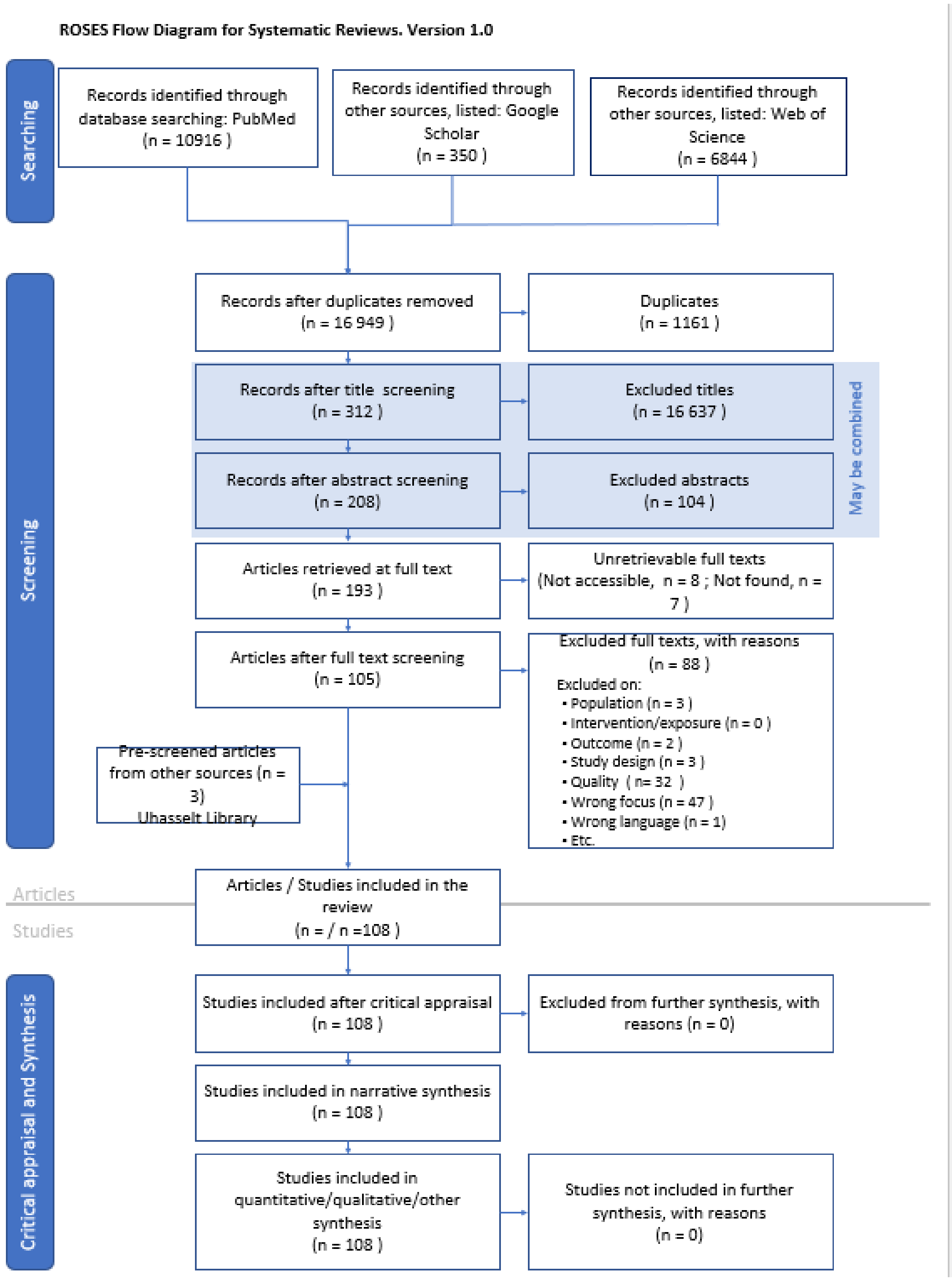

Figure 1: ROSES flow diagram (Haddaway et al., 2017)

Results

What COVID-19 measures were imposed (on companies) to get the global lockdown operational?

During the COVID-19 pandemic, many measures were imposed not only on businesses, but also on people to stop the spread of the SARS-CoV-2 virus. The measures were introduced to reduce the number of infections but also to enable hospitals to treat everyone with the same care. Many non-essential businesses had to close their doors during the worst stages of the pandemic, and even if they were allowed to reopen or remain open, strict rules such as wearing masks and keeping their distance had to be followed. In this section, I discuss the following non-pharmaceutical measures: personal protective equipment (PPE), hygienic measures, travel restrictions, closings, contact tracing, stay at home, isolation and quarantine. For each measure, I also discuss whether or not they were effective and, finally, I identify the different COVID-19 strategies that countries used.

Before I give an overview of all major measures taken during the COVID-19 pandemic, I think it is important to define the meaning of lockdown in this thesis. Lockdown is used in this paper for all types of emergency measures such as quarantine, travel restrictions, closure of services and industry, and other emergency measures.

Closing of non-essentials

During the worst stages of the pandemic, governments around the world decided it was necessary to close non-essential businesses. Schools, universities, bars, restaurants, museums, swimming pools and companies had to close and mass gatherings were banned as well.

To mitigate the spread of COVID-19, many governments of European countries closed schools in March 2020 and reopened them after the summer holidays until autumn. The reopening of schools had three reasons. First, there was not enough evidence of transmission from children to adults and younger children seemed to spread the virus less. Second, some suggested that closing schools was harmful to children. School closures caused issues such as mental health problems and weight gain. Third, good education is very important for children. When schools reopened, measures were taken to reduce the spread of COVID-19. In nurseries, the most common measures taken were hygiene measures, exclusion of sick children and cleaning of surfaces. In primary schools, the most commonly taken measures were ventilation, testing of children and social distance. In secondary schools, face masks and cancellation of physical education were added to the most common measures (Jansen et al., 2021).

Not all researchers agree that school closure was such an effective measure. Gianino et al. (2021) examined the effect of school closure on incidents of COVID-19 in the UK, Spain, Italy and Germany. They concluded that there was no correlation between school closure and incidents (Gianino et al., 2021). In contrast, Davies et al. (2020), Ayouni et al. (2021) and Liu et al. (2021) concluded that school closure did mitigate the spread of COVID-19. According to Davies et al. (2020), school closures reduced deaths from 120 000 to 65 000 and the need for ICU beds from 53 000 to 29 000 in the UK. However, when grandparents care for the child younger than 15 years during the closure, the effect of closing schools is almost entirely eliminated (Davies et al., 2020).

During the COVID-19 pandemic, many other workplaces also had to close temporarily. Even if they remained open or were allowed to reopen, certain control and prevention measures had to be taken, e.g. PCR testing, contact tracing, personal protective equipment (Ingram et al., 2021). Ishimaru et al. (2021) examined the measures taken in companies based on the difference in company size in Japan. The most common measures taken in workplaces in Japan were wearing masks, sick employees were not allowed to come to work, and work-related events were cancelled. 90% large-scale companies and 40% micro and small-scale companies applied these measures. Remote working was also a measure strongly recommended by the government. However, remote working was not well applied in Japan, especially in micro- and small-scale enterprises. Only 20% of micro- and small-scale enterprises encouraged remote working (Ishimaru et al., 2021).

Closing workplaces was quite effective, according to Gianino et al. (2021). They found a significant correlation between closing workplaces and incidents in the UK. Ingram et al. (2021) examined the effectiveness of workplace prevention measures. They concluded that placing workers in small work bubbles was an effective way to reduce workplace transmission. Wearing masks among staff was not very effective when carried out alone. However, the combination of masks and physical barriers was quite effective (Ingram et al., 2021).

The COVID-19 crisis also caused restrictions on gatherings. We were no longer allowed to gather for recreational or sports purposes. The closure of pubs, restaurants and sports facilities had a major impact on the economy and way of life (De Bruin et al., 2020). Moreover, the government also restricted private gatherings. For example, during certain periods of the corona crisis, gatherings of more than 10 people were not allowed. Ayouni et al. (2021) and Niu et al. (2021) both came to a similar conclusion. They found that restrictions on mass gatherings were effective in reducing the spread of COVID-19 (Ayouni et al., 2021). In fact, according to Niu et al. (2021), banning public events led to the greatest reduction in the R-ratio.

The following sections elaborate on all the measures imposed on businesses and people.

Personal protective equipment and hygienic measures

Hygiene measures were one of the first measures introduced to combat the spread of COVID-19. We were advised to wash our hands thoroughly, cough into our elbow, avoid touching surfaces and contaminated materials as much as possible (De Bruin et al., 2020). Doung-ngern et al. (2020) investigated the effectiveness of hand washing in Thailand and they concluded that hand washing can indeed reduce the risk of COVID-19 infection. Teslya et al. (2020) came to the same conclusion, hand washing is a crucial measure to control the epidemic. Hand washing by disease-aware people can delay the peak of the epidemic, flatten the curve and reduce the number of infections (Teslya et al., 2020). Hygiene might even have prevented the pandemic from ever breaking out. The coronavirus outbreak probably started at a wet market in Wuhan. At wet markets, animals are often slaughtered on the spot which leads to people being exposed to animal fluids and consequently animal viruses such as the SARS-CoV-2 virus (De Bruin et al., 2020).

During the pandemic, we also used personal protective equipment, such as masks, to protect ourselves from the virus. At the beginning of the SARS-CoV-2 virus outbreak, it was not really clear whether it was necessary to wear a face mask or not. Moreover, many countries had a limited supply of face masks and kept this limited supply mainly for health workers. As the pandemic got worse, a lot of countries decided that wearing a face mask when leaving home was mandatory. People had to wear masks in places like public transport, offices, schools, supermarkets and pharmacies (De Bruin et al., 2020). It also became clear that wearing a face mask was an effective measure against the spread of the virus (Ayouni et al., 2021; De Bruin et al., 2020; Doung-ngern et al., 2020; Ford et al., 2021; Teslya et al., 2020). Ford et al. (2021) investigated whether wearing a mask by the general public in community settings is an effective measure. They conducted a systematic review that included twenty-one articles, and all of these studies concluded that wearing a face mask was an effective measure to control the coronavirus. Wearing masks can reduce incidence, hospitalisation, mortality or a combination of these outcomes. The conclusion of Doung-ngern et al. (2020) was similar to the conclusion of Ford et al. (2021). Doung-ngern et al. (2020) conducted a case-control study in Thailand. When people wore masks all the time during the contact, the risks of infection became lower. The type of mask people wore during contact did not reduce the risk of infection (Doung-ngern et al., 2020). Personal protective equipment was effective not only for the general public, but also for health workers. Health workers were often exposed to infected people, and in Wuhan, China, it was found that infection rates among health workers were higher than among the general public in a period without strong public health measures. Thanks to increased awareness, wider use of personal protective equipment and strong public health measures, there were no new infections among health workers and infection rates decreased overall. Protection of health workers thus seems very important (Ayouni et al., 2021).

Finally, not only masks were used to combat the spread of COVID-19, mostly in supermarkets and offices they also used physical barriers. Ren et al. (2021) investigated the appropriate barrier height to limit aerosol particle dispersion in an open office. The open office environment was equipped with a good ventilation system and air supply rate. They concluded that a barrier height of at least 40 cm above the desk is necessary to prevent the cough flow of an infected person. The most recommended height of physical barriers was between 60 and 70 cm. A barrier of 70 cm can reduce the risk of infection by 72%. However, if the physical barrier is more than four metres away from the ventilation exit, the effect of the barrier is not significant (Ren et al., 2021).

Travel restrictions

Among the measures introduced by the government to limit the spread of the COVID-19 virus were travel restrictions. During the COVID-19 period, there were travel and entry restrictions, border measures and mandatory quarantine for people travelling from highly infected countries (Ayouni et al., 2021; Gianino et al., 2021). Some countries even banned travel or banned people coming from a particular country (Gianino et al., 2021; Girum et al., 2021). According to Ayouni et al. (2021), all these travel restrictions helped to limit the spread of COVID-19 virus. Girum et al. (2021) and Grépin et al. (2021) agree with Ayouni et al. (2021). A travel ban is an effective measure to limit the spread of COVID-19. But travel bans should be mandatory, initiated early on a large scale and for a longer period. In China, a travel ban prevented 70.5% of cases carried out. A combination of a travel ban and social distancing would even enhance the effect of a travel ban (Girum et al., 2021; Grépin et al., 2021). In contrast, the conclusion of Gianino et al. (2021) is more nuanced. They argued that the effectiveness of travel restrictions varies by country. The government not only imposed international travel restrictions, but also restricted internal travel between cities/regions and the use of public transport. Gianino et al. (2021) found a decrease in the number of incidents after 30 days in Germany when the internal movement of people between cities is restricted. Grépin et al. (2021) also considered domestic travel measures taken within China. They investigated whether the travel restrictions in Wuhan affected the domestic export of cases to other parts of China. The travel ban in Wuhan led to a significant reduction in COVID-19 transmission across the country. As with the international travel bans, the timing of the introduction of the domestic travel bans also seems to be of great importance. Early implementation of the domestic travel restriction dramatically increases the effectiveness (Grépin et al., 2021; Kraemer et al., 2020).

It seems that travel restrictions were an effective measure to limit the spread of COVID-19 and consequently reduce the number of new people affected. However, travel restrictions have a huge impact on the economy when introduced for a longer period (Girum et al., 2021; Grépin et al., 2021).

Contact tracing

Contact tracing was also used to monitor the spread of the SARS-CoV-2 virus. They use contact tracing to identify and notify people exposed to someone with SARS-CoV-2 virus. Contract tracing proved to be an effective measure to prevent the spread of COVID-19. However, it is very important that contact tracing is applied early, has wide coverage and is integrated with other measures such as quarantine and screening (Ayouni et al., 2021; Girum et al., 2020). According to Kucharski et al. (2020), the combination of self-isolation and household quarantine would reduce average transmission by 37%. When manual tracing of all contacts is added to the combination of self-isolation and household quarantine, the average transmission reduces by 64%. Thus, from these figures, we can conclude that contact tracing can be a fairly effective measure to stop the spread of COVID-19 (Kucharski et al., 2020).

Apps were used in many countries to assist in the effectiveness of contact tracing. Fan et al. (2022) investigated the quality of twenty COVID-19 management apps in China. Not all these apps were used for contract tracing, some apps offered only news about COVID-19 or scientific knowledge about the prevention of COVID-19 (Fan et al., 2022). According to Kucharski et al. (2020), contact tracing through apps is an effective measure to stop the spread of COVID-19. However, it is less effective than the manual tracing of all contacts. As mentioned earlier, the combination of self-isolation, household quarantine and manual contact tracing would reduce average transmission by 64%. The combination of self-isolation, household quarantine and app-based tracing only reduces average transmission by 47%. This is because tracing via apps requires each party involved to have installed and also use the app (Kucharski et al., 2020). Contact tracking apps can be effective, but we should not forget that they also increase the potential risk of personal data leakage. Software developers should therefore ensure that consumers' personal data are protected (Fan et al., 2022).

Stay at home

During some parts of the COVID-19 period, governments advised or forced us to stay at home as much as possible. Our individual movements were restricted even if we were not sick or did not show signs of illness (Davies et al., 2020). There were limitations on using one's own car and bicycles. In some countries, walking and running outside was even restricted. For example, you were only allowed to walk outside if you had a dog or you were not allowed to run in groups of more than two people (De Bruin et al., 2020). If you had to go out to buy food, you were advised to practice social distancing. This meant keeping your distance from other people and avoiding crowded places like busy supermarkets (Teslya et al., 2020). On the other hand, if you were sick or showed signs of illness, you were not allowed to leave the house either. Symptomatic persons had to isolate themselves for seven days or more. People who came into close contact with symptomatic cases had to be quarantined (Kucharski et al., 2020; Ayouni et al., 2021). All these measures were taken to reduce people's contacts.

Jarvis et al. (2020) investigated the effect of physical distance measures in the UK by asking adults about their contact patterns on the previous day. The physical distance measures were quite effective, as the researchers concluded that questionnaire participants reduced their number of contacts by 74%. If a similar pattern could be observed for the entire United Kingdom, it would mean that the reproductive number would be less than one. Which would lead to a decrease in infections in the coming weeks (Jarvis et al., 2020). Teslya et al. (2020) also concluded that social distancing measures are quite effective. If they are taken at an early stage of the epidemic, the health system may have more time to prepare for an increasing number of COVID-19 cases.

Stay-at-home policies are one of the most effective policies to combat the spread of COVID-19. It can reduce incidence and mortality by half, but stay-at-home policies also have a huge impact on the economy. If people are allowed to leave their homes only when necessary, they have to work at home as much as possible, and some people like waiters cannot work at home. That is why most countries try to avoid long-term stay-at-home policies (Girum et al., 2021).

Quarantine of exposed individuals could prevent 44 to 81% of cases and 31 to 63% of deaths, according to Girum et al. (2020). Self-isolation of symptomatic people is also an effective way to reduce the spread of COVID-19 (Ayouni et al., 2021). It is reported to reduce transmission by 29% (Kucharski et al., 2020). In many cases, however, effectiveness can be increased by combining different measures. For example, a combination of quarantine, isolation, contact tracing and/or a travel ban would increase effectiveness (Ayouni et al., 2021; Girum et al., 2020). If the level of screening and contact tracing is not high enough, isolation is not really an effective measure because screening programmes miss 75% of cases (Girum et al., 2020). According to Davies et al. (2020), who examined non-pharmaceutical interventions in the UK, self-isolation is also not really sufficient to control the spread of COVID-19 and the increasing need for ICU capacity. Kucharski et al. (2020) concluded that the combination of isolation and tracking strategies is more effective than mass testing or self-isolation alone. As mentioned, self-isolation within the household would reduce average transmission by 29% and self-isolation outside the household by 35%. Self-isolation, household quarantine and tracing of all contacts would reduce transmission by 64% (Kucharski et al., 2020).

Overall, we can conclude that most measures are reasonably effective, but they are even more effective when combined. Moreover, we should not forget that the effectiveness of many measures depends on their compliance. According to Gianino et al. (2021), young adults and adolescents are reluctant to follow measures such as hand washing, self-isolation and social distancing.

Country differences

The COVID-19 crisis was a global pandemic. Yet each country handled the pandemic differently. This section highlights some of these differences.

Jansen et al. (2021) investigated the difference in COVID-19 measures in schools in 19 European countries. First, they used a questionnaire to examine the number of measures taken per country for childcare, primary and secondary education. They found that the most measures were taken in France, Germany, Greece, Poland and Spain and the least in Bosnia-Herzegovina, the Czech Republic, the Netherlands and Norway. Moreover, they compare in detail the different measures taken in schools in different countries. All 19 countries have a policy on individual hygiene in schools and in most countries it is compulsory, except in Norway and Sweden. In Greece, individual hygiene is compulsory for childcare and primary school, but not for secondary school. The Netherlands and Portugal are the only two countries where sick children are not excluded from childcare and/or primary school. In the Netherlands, only children with severe symptoms such as fever are excluded from childcare or primary school. Most countries do not have policies for closing childcare and primary schools, and if they have a policy, it is often not a mandatory policy. For secondary school closures, only Croatia and Switzerland have a policy. Some other countries also have policies to close high schools in some cases. But this policy is only mandatory in the Netherlands (Jansen et al., 2021).

Differences in Nordic responses to COVID-19 were examined by Saunes et al. (2021). They found quite a few similarities between the measures in Denmark, Finland, Iceland, Norway and Sweden, but the countries also showed some differences in implementation and outcomes (Saunes et al., 2021). Perhaps one of the biggest differences in the measures taken in the Nordic countries is that in Sweden, people were never required to put on a face mask (Ludvigsson, 2020; Saunes et al., 2021). Furthermore, in spring 2020, Denmark, Finland and Norway adopted national measures such as restrictions on international travel, closure of schools and non-essential businesses to limit the spread of COVID-19. In Finland and Norway, domestic travel was also restricted for a short period. In Sweden and Iceland, they restricted international travel. In Iceland, for example, travel to high-risk areas was restricted. No curfews were imposed in any of the Nordic countries and there was a switch to digital and remote working. In Denmark, Finland and Norway, schools reopened at the end of April. In Iceland, schools were never closed to children ages 6 to 16 (Saunes et al., 2021). In Sweden, schools and universities were closed to children over 16 for three months (Ludvigsson, 2020). Furthermore, Sweden made recommendations to its population, such as working from home and avoiding public transport. Contact tracing strategies also differed between the Nordic countries. At the beginning of the pandemic, for example, the Danes had to track down their own recent contacts. Self-isolation was mandatory in all Nordic countries. Quarantine in case of contact with the virus was mandatory in all Nordic countries except Sweden. According to Saunes et al. (2021), Sweden had a higher number of incidents and deaths than the other Nordic countries in 2020. However, according to Ludvigsson (2020), the number of deaths is still lower than in some European countries with widespread lockdowns.

Belgium is one of the European countries that did have some kind of lockdown. The lockdown measures in Belgium started around mid-March 2020. The lockdown period in Belgium can be divided into four phases. During the first phase, schools, restaurants and cafes had to close and gatherings were not allowed. The second phase included social distancing measures, teleworking, closure of non-essential businesses and travel restrictions. In the third phase, restrictive measures were extended, Belgium closed the border and a national screening was introduced. In the fourth phase, all the above restrictive measures were maintained until 3 May. From 4 May, the government began to gradually reduce the number of restrictions (He et al., 2020).

Haider et al. (2020) examined the lockdown measures taken in the following sub-Saharan African countries: Ghana, Nigeria, South Africa, Sierra Leone, Sudan, Tanzania, Uganda, Zambia and Zimbabwe. Between these nine African countries, there were some similarities but also some differences. Tanzania had the fewest measures and South Africa and Uganda had the strictest restrictions. All nine countries restricted international travel. In Tanzania, however, international travel restrictions had already been lifted in May. Sierra Leone and Tanzania were the only countries where restaurants, cafes and businesses were not closed. However, schools, colleges and universities had to close in all nine countries. All of the countries surveyed also had restrictions on meetings, and except for Zambia and Tanzania, curfews were imposed. The sub-Saharan African countries also introduced measures such as hygiene measures, active case detection, isolation, contact tracing and quarantine, to varying degrees. From mid-April 2020, all countries started easing restrictions. In Ghana, for example, workplaces and businesses were reopened and in Zambia, restaurants, gyms and casinos were allowed to reopen on 8 May, but bars and taverns were still not allowed to open their doors (Haider et al., 2020).

Finally, we look at the measures taken in China since the COVID-19 pandemic began there. Wuhan and 16 adjoining cities in the Hubei province were placed in a cordon sanitaire on 23 January 2020. Transportation in and out of Wuhan was no longer allowed. They also extended the Spring Festival holiday by eight days so they could keep schools closed a little longer. After the holiday ended, Beijing, Guangzhou, Shenzhen, Shanghai, Hangzhou and Chengdu introduced social distancing and mobility measures, such as residential areas that only residents were allowed to enter. It was also mandatory to wear a face mask, it was forbidden to travel by bus or metro, public gatherings were prohibited and infected people had to isolate themselves. On 17 February, Guangdong, Jiangsu, Zhejiang and Shanghai were reopened. In Wuhan and Hubei, restrictions were relaxed only in mid-March (Leung et al., 2020; Tian et al., 2020).

How did these measures influence the environment: comparison before COVID-19, during COVID-19 lockdown, after the lockdown?

Now that we know all the measures to get the global lockdown operational. We can discuss the impact of the non-pharmaceutical measures on the environment. In this section, I look at the impact of the COVID-19 measures on air quality, waste management, water quality and noise.

Air quality

The COVID-19 measures had quite an impact on air quality. The main sources of air pollution are power generation, industry, traffic and residential energy use (Venter et al., 2020). As mentioned earlier, during the COVID-19 crisis, governments worldwide imposed measures to stop the spread of COVID-19. Non-essential businesses had to close, movement of people was restricted and international borders were closed. This caused a reduction in traffic and industry, both causes of air pollution. The COVID-19 period was thus the ideal period to look at the effect of traffic, industry and people on air pollution. In this section, I examine the impact of the COVID-19 measures on the following elements: CO_2, CO, O_3 $PM_{2.5}$, PM_{10}, SO_2, NO_2. I discuss the change in these elements for Europe, Asia, the Middle East, North America, South America and Oceania.

Sulphur dioxide (SO_2)

Sulphur dioxide is a gas known for its foul odour. Sulphur dioxide is a highly reactive gas that can come from industrial sources burning fossil fuels or from natural sources such as volcanoes, sea spray and organic decay. SO_2 is also quite harmful to humans, as it can cause nasal, throat and lung disorders and cardiovascular disease (Albayati et al., 2021; Kaied et al., 2021). According to Foster et al. (2020), global SO2 decreased by about 20% during the COVID-19 lockdown.

Europe

Guevara et al. (2022) examined changes in SO_2 levels in all European Union countries plus the United Kingdom for the period between 1 January and 31 December 2020. SO_2 started to decline in March 2020. Local and national lockdowns also began in March. The largest decrease in SO_2 was observed from late March to early April. This period also corresponds to the period when the COVID-19 restrictions were at a maximum. SO_2 levels began to recover in late April when restrictions were also relaxed. By mid-September, SO_2 levels again reached the same levels as before the lockdown. In the period from January to December, an overall reduction of 4.6% SO_2 was recorded in Europe. In Malta, the relative decline in SO_2 was the largest (Guevara et al., 2022).

The Middle East

During the corona crisis, SO_2 levels in the Middle East also changed. Kaied et al. (2021) observed a considerable drop in SO_2 concentrations in the emirate of Ajman. In May 2020, SO_2 concentrations dropped by 60% compared to the same period in 2019 (Kaied et al., 2021). In Jordan, Dabbour et al. (2021) came to a similar conclusion. They examined air quality in Jordan's three largest cities (Amman, Irbid and Zarqa) during the lockdown. SO_2 reduction was the highest in Zarqa, followed by Amman and then Irbid. In Zarqa, there are a lot of industries that use fuel with high sulphur and nitrogen content. During the lockdown, these industries had to close down. This may explain the sharp drop in SO_2 concentrations in Zarqa (Dabbour et al., 2021). In Israel, a 50% drop in SO_2 emissions was measured during lockdown (Klein et al., 2022). Thus, in the Middle East, too, we can conclude that the actions taken to stop the spread of COVID-19 also had a positive effect on SO_2 concentrations.

However, it is also very important to consider the direct relationship between meteorological data and SO_2 concentrations before and after the COVID-19 period. Dabbour et al. (2021) investigated the correlation of meteorological data variables such as humidity, wind speed, mean temperature and pressure of the three largest cities in Jordan with the amount of daily pollutants emitted. Dabbour et al. (2021) concluded three things. First, the meteorological data of the three cities differ in their effect on SO_2 concentration. Second, the meteorological data and lockdown of the three cities differ in their effect on SO_2 concentration. Third, meteorological factors must be taken into account when evaluating the effects of pollutant source changes on air quality during the COVID-19 lockdown. Indeed, researchers found that meteorological data contributed significantly to the observed changes in air pollutants (Dabbour et al., 2021).

Asia

Shehzad et al. (2021), Sathe et al. (2021) and Singh et al. (2020) investigated the change in SO_2 concentrations in India. Sing et al. (2020) and Sathe et al. (2021) reached a fairly similar conclusion regarding SO_2 concentrations in India. According to Singh et al. (2020), SO_2 levels increased slightly in some regions, but also decreased significantly in others. As mentioned, the most common source of SO_2 is the burning of sulphurous fuels such as coal and diesel. In India, SO_2 is mostly generated by coal-fired thermal power plants. Singh et al. (2020) examined the changes in SO_2 emissions in Central, North-West, IGP (Indo Gangetic plain) and South India. During the lockdown in India, SO_2 concentrations decreased slightly, except in South India (Singh et al., 2020). Sathe et al. (2021) also concluded that SO_2 levels did not show a clear downward trend and even observed an increase in SO_2 concentrations in Mumbai, Bengaluru and Kolkata.

In Delhi, one of India's megacities, Singh et al. (2020) observed a 23% decrease in SO_2 concentrations. The same was observed by Shehzad et al. (2021) before the lockdown, SO_2 concentrations ranged from 25 $\mu g/m^3$ to 75 $\mu g/m^3$. However, during the lockdown, SO_2 levels were only 20 $\mu g/m^3$. Sathe et al. (2021) observed a 29% reduction in SO_2 emissions. The reduction in SO_2 concentration in Delhi can be explained by reduced industrial activity and reduced power plant operation. In Delhi, more than 85% of the SO_2 concentration comes from industrial activities such as thermal power plants. In contrast, in Mumbai, another megacity in India, Sathe et al. (2021) observed an 81% increase during the lockdown period. The increase in SO_2 concentrations in Mumbai during the closure period may have several causes. First, some heavy industries were kept open during the lockdown period. Second, some ships were spotted in ports near Mumbai. Third, emissions could be higher due to more cooking activities at home (Sathe et al., 2021). However, Shehzad et al. (2021) observed a decrease in SO_2 levels in Mumbai, but the decrease in SO_2 was lower than the decrease in other pollutants. Further, they also argued that the improvement in air quality in Mumbai and Delhi was only temporary (Shehzad et al., 2021).

Singh et al. (2020) also investigated the diurnal variations of pollutants. The diurnal variations of pollutants are determined by local emissions, meteorological conditions and diurnal and nocturnal chemistry. The researchers compared daily variations of pollutants between the years 2017-2019 and 2020 for Central, North-West, IGP and South India. In IGP and central regions, they observed a morning peak in the daily variation of SO_2 during the years 2017-2019. They also observed the highest concentration of SO_2 in the IGP region and the lowest in South India during the afternoon. During the lockdown, the IGP region showed a large decrease in SO_2 concentration during the morning hours. In the afternoon, the decline in SO_2 levels became negligible. In South India, an increase in SO_2 levels was observed in some cities. The cause of this increase could be due to the decrease in SO_2 oxidation due to a decrease in O_3 concentration in the presence of NaCl particles (Singh et al., 2020).

In China, all researchers agree that SO_2 concentrations decreased due to COVID-19 measures (Fan et al., 2020). In East China, they compared SO_2 concentrations in the first three months of 2019 with those in the first three months of 2020 and saw a small decrease (Filonchyk et al., 2020). In the Guanzhong Basin, the most economically developed area in northwest China, they also observed a change in SO_2 levels. SO_2 levels in Tongchuan and Weinan are the highest because they have multiple coal mines. The lockdown period led to a 31% drop in Tongchuan city (Zhang et al., 2020). SO_2 levels also fell in the Yangtze Delta region, an economic engine of modern China. SO_2 concentrations decreased by 20.4% during the first-level response period (from 24 January to 25 February) and by 7.6% during the second-level response period (from 26 February to 31 March) (Li et al., 2020). SO_2 levels in China thus decreased during the lockdown period. However, it should be remembered that this is only a temporary drop in SO_2 emissions (Filonchyk et al., 2020).

Kanniah et al. (2020) investigated the SO_2 situation in Malaysia. They differentiated based on location. In urban areas, they saw a reduction between 9 and 20%, and in suburban areas even between 17 and 19% in 2020. In industrial areas, however, there was no reduction in SO_2 concentration because power plants had to remain in operation. Kanniah et al. (2020) also noted that SO_2 levels, especially in rural areas, depend on local/regional meteorology and downwind of urban and industrial zones (Kanniah et al., 2020).

Nitrogen dioxide (NO_2)

Nitrogen dioxide is a reactive gas that is clearly visible in polluted cities as it leaves a radish-brown layer on surfaces. Sources of NO_2 are industry, transport facilities, heating activities, gas stoves, smoking and heaters. NO_2 is harmful to human airways and also causes the formation of ozone and particulate matter (Albayati et al., 2021). The COVID-19 measures caused a decrease in global NO_2 concentrations (Cooper et al., 2022; Forster et al., 2020). Unfortunately, the decline in NO_2 concentrations is also a temporary one and if we want to prolong this decline, we need to make efforts to protect the environment (Albayati et al., 2021).

North America & South America

NO_2 concentration in the USA was assessed by Albayati et al. (2021), Liu et al. (2021) and Sulaman et al. (2020). Researchers examined the decrease in NO_2 levels in 28 tracking air pollution stations in the USA and found a decrease of up to 49%. The decrease in NO_2 concentrations was greatest in places with high population density (Albayati et al., 2021). The reduction in NO_2 emissions was also noted by Sulaman et al. (2020) who investigated NO_2 concentrations in the north-eastern part of the USA by looking at NASA satellite images. They concluded that NO_2 concentrations had decreased by about 30%. In California, Liu et al. (2020) investigated the spatiotemporal patterns of NO_2. They observed a 38% reduction in ground-level NO_2 concentration during the lockdown period. However, they observed an increase in NO_2 near intersections of national highways in densely populated areas, while NO_2 levels decreased near large power plants. During the COVID-19 lockdown, people had to stay at home more often, so the increase may have been caused by the increase in fuel combustion at home. In the residential areas, people also started ordering more items such as food and groceries. This is also a reason why NO_2 concentrations increased in residential areas (Liu et al., 2020). The conclusion of Lui et al. (2020) somewhat contradicts the findings of Albayati et al. (2021) who stated that NO_2 reductions were greatest in densely populated locations.

In Canada, they also observed a decrease in NO_2 emissions. According to Mashayekhi et al. (2021), seasonal decreases in daily NO_2 were higher during the lockdown period compared to the pre-lockdown period. In Montreal, Toronto, Calgary and Vancouver, the four major cities of Canada, drops in NO_2 levels between 31% and 34% were observed (Mashayekhi, 2021). In South America, namely Brazil, NO_2 concentrations also decreased. A reduction of 54.3% was observed in the parts of São Paulo heavily affected by traffic. However, in the less traffic-affected areas, the reduction in NO_2 levels during the lockdown was lower (Albayati et al., 2021).

Europe

In Europe, researchers too observed a reduction in NO_2 levels (Guevara et al., 2022). In Spain, satellite images showed a reduction between 20 and 30%. The reduction was particularly noticeable in large cities such as Madrid, Barcelona and Seville (Sulaman et al., 2020). Similar results were noted by Querol et al. (2021). During the full lockdown, traffic in Spain dropped by as much as 80%. The decrease in traffic caused a large drop in NO_2 emissions. In Barcelona, Seville and Madrid, for example, a decrease between 50-56% was observed. In Valencia, even a 69% decrease was observed during the restriction period. During the relaxation period in Spain, reductions in NO_2 emissions were still noticeable. This is probably because during the relaxation period, traffic in cities like Barcelona and Madrid still experienced reductions (Querol et al., 2021). Petetin et al. (2021) also found a relationship between the strictness of the lockdown and the reduction in NO_2 emissions. During the most stringent phase of the lockdown, NO_2 reduction was also greatest (Petetin et al., 2021).

In Italy, researchers similarly observed a 20-30% reduction in NO_2 emissions on satellite images due to a drastic reduction in traffic during the lockdown (Sulaman et al., 2020). For example, in northern Italy, namely in the city of Reggio Emilia, a sharp reduction of up to 82% in the number of moving vehicles was observed. The reduction in traffic caused a decrease of more than 30% in NO_2 levels in the city of Reggio Emilia (Marinello et al., 2020). In the urban area of Palermo, researchers even observed a 50% reduction during the lockdown period (Vultaggio et al., 2020).

In France, satellite images likewise show a drastic reduction in NO_2 levels in March 2020, especially in Paris (Sulaman et al., 2020). Menut et al. (2020) studied NO_2 levels across Western Europe. They observed whether air quality changed during the lockdown, taking into account meteorological conditions, and concluded that NO_2 levels decreased between 30 and 50% in Western Europe (Menut et al., 2020). Schneidemesser et al. (2021) assessed the situation in Berlin. In Berlin, car traffic decreased by 33% on weekdays and 47% on weekends. Truck traffic also recorded a decrease of 20% on weekdays and 29% on weekends. As mentioned, traffic is a major cause of air pollution, so it is not surprising that NO_2 levels fell during the lockdown. A 39% decrease was observed on weekdays and even a 42% decrease in weighted NO_2 concentrations on weekends (Schneidemesser et al., 2021).

The Middle East

In the Middle East, NO_2 concentrations fell due to the reduction in traffic as a result of COVID-19 restrictions such as the closure of businesses. In Jordan's three largest cities, namely Amman, Irbid and Zarqa, researchers observed a decrease in NO_2 emissions. The largest reduction in NO_2 was found in Zarqa due to the closure of industries using fuel with high nitrogen content (Dabbour et al., 2021). In Iraq, researchers found reductions of up to 40% during the lockdown period that began in January and ended in July 2020. The reductions were particularly noticeable in major cities such as Baghdad, Basra, Najaf and Erbil. Before the COVID-19 restrictions, the highest concentrations of NO_2 were measured in Baghdad and Basra. This is probably due to the fact that Baghdad is a densely populated city with a lot of traffic pollution and industrial activities. Basra is the largest city in southern Iraq and has oil fields and consequently gas burning activities. In both Basra and Baghdad, NO_2 levels dropped significantly during the lockdown period that began in April and ended in July 2020 (Hashim et al., 2021).

In Egypt, researchers compared NO_2 concentrations in 2020 with the same period in 2015-2019. Containment measures taken in Egypt in March 2020 reduced NO_2 emissions. In Egypt's largest city, Cairo, NO_2 levels fell 15% and in the second largest city, Alexandria, they recorded a 33% drop.

From 1 April to 1 May 2020, factories reopened to produce products for the Ramadan. This caused a slight increase in NO_2 levels. During the Ramadan period, NO_2 concentrations only decreased 13% in Cairo and 9% in Alexandria (Mostafa et al., 2021). Mostafa et al. (2021) argues that the improvement in air quality is not sustainable. In the emirate of Ajman, researchers have also measured reductions between 40% and 60% in ground-level NO_2 (Kaied et al., 2021).

Asia

In China, the origin of COVID-19, researchers too found significant reductions in NO_2 emissions due to reductions in economic activities and traffic (Fan et al., 2020; Wang & Su, 2020). NO_2 concentrations decreased by about 30% during the pandemic in early 2020 (Chu et al., 2021). The decline in NO_2 levels first started in Wuhan and then spread throughout the country. This is probably because the COVID-19 outbreak started in Wuhan and consequently the first COVID-19 measures were implemented in Wuhan. Thereafter, other regions in China also started to implement control measures and consequently their NO_2 levels also started to decrease (Wang & Su, 2020).

The NO_2 reduction measured in Wuhan city was 53% during the pandemic in early 2020. In the entire Hubei province, of which Wuhan is the capital, a 50% decrease in NO_2 emissions was recorded (Chu et al., 2021). A 30% drop in NO_2 concentrations was measured in eastern China. (Filonchyk et al., 2020). They recorded a decrease between 27.2% and 45.1% in NO_2 concentrations in the Yangtze River Delta area, mainly located in eastern China (Li et al., 2020). NO_2 levels in the Guanzhong basin decreased by 52% during the most severe period of the closure (Zhang et al., 2020). However, Filonchyk et al. (2020) also argue that the improvements in air quality were only temporary.

In India, researchers too observed a decrease in NO_2 emissions during lockdown (Biswal et al., 2021; Sathe et al., 2021; Singh et al., 2020). They found decreases in NO_2 levels ranging from 30 to 70% (Singh et al., 2020). However, in some parts of India, NO_2 levels were elevated due to fires that occurred during the lockdown period (Biswal et al., 2021). In Delhi and Mumbai, India's two most populated cities, researchers also measured reductions in NO_2 emissions ranging from 46% to 61% (Sathe et al., 2021; Shehzad et al., 2021). In Delhi, they recorded the maximum reduction in NO_2 levels. This is probably because in Delhi, the transport sector, which was greatly reduced during the lockdown, accounts for 85% of NO_x emissions (Sathe et al., 2021).

Researchers in other parts of Asia likewise detected changes in NO_2 emissions due to COVID-19 restrictions. In Malaysia, for example, a reduction between 63 and 64% was observed in urban areas during the lockdown period. In rural areas, researchers measured only a 26-34% reduction (Kanniah et al., 2020). In Indonesia, full lockdowns were not implemented for fear of economic recession. However, social restrictions and partial lockdowns were introduced to prevent the spread of COVID-19. Despite the fact that there were no full lockdowns in Indonesia, they still observed significant reductions in NO_2 emissions in Malang City and Surabaya City (East Java province). In Malang City, NO_2 concentrations decreased by 38% and in Surabaya City by 28% (Purwanto et al., 2022).

Oceania

A reduction in NO_2 emissions was also observed in Oceania. For example, in Sydney (Australia), NO_2 levels decreased by 7.9% and in New Zealand by 50% (Yang et al., 2022).

Ozone (O_3)

Ozone is an unstable gas composed of three oxygen atoms. The gas protects humans from the sun's ultraviolet radiation. Ozone is found in the atmospheric layers, more specifically between the troposphere and the stratosphere. Although ozone protects us from ultraviolet radiation, an increase in ozone concentration has negative effects on humans. It can cause asthma and bronchitis. Low-level ozone is created by the reaction of industrial and transport discharges with sunlight (Albayati et al., 2021). During the COVID-19 lockdowns, researchers measured a global increase in O_3 (Venter et al., 2020). This increase is mainly caused by the reduction of NO_x. A reduction in NO_x causes a decrease in O_3 titration by NO, leading to an increase in O_3 levels (Mashayekhi et al., 2021; Sicard et al., 2020).

North America & South America

In Canada, they also observed an increase in O_3 due to the decrease in NO_x concentrations. In Montreal, Toronto, Calgary and Vancouver, an average 2-5% increase in O_3 surface concentrations was measured. The researchers even observed a 21% increase in urban city centres, while a 0.3% decrease was observed in suburban areas. The small decrease in O_3 in the suburbs can be explained by the smaller decrease in NO_2 in the suburbs (Mashayekhi et al., 2021). In Brazil, they measured an increase in O_3 levels in São Paulo and Rio de Janeiro. In São Paulo, they observed an increase of about 30% (Albayati et al., 2021).

Europe

Researchers have also observed an increase in ozone in the city of Reggio Emilia in Italy. According to Marinello et al. (2020), O_3 levels increased by 13% compared to 2019 levels. O_3 is a secondary photochemical pollutant. The formation of O_3 increases because of the following reasons: increase in temperatures, increase in solar radiation and reduction of NO concentrations during the lockdown period (Marinello et al., 2020). Sicard et al. (2020) also measured increases in O_3 in Rome and Turin. In Rome, O_3 levels rose by 14% and in Turin by as much as 27%. In Nice (France), O_3 emissions increased by about 24% (Sicard et al., 2020). In Spain, however, some cities show an increase in O_3 levels, others a decrease or no relevant changes. For example, Valencia, Badajoz and Zaragoza showed a decrease in O_3 levels between 4 and 13%, while Malaga, Barcelona and Madrid showed no decrease or a small increase (Querol et al., 2021). In Berlin, the researchers observed a 22% increase in O_3 levels during weekdays. On weekends, however, O_3 concentrations did not change. This is probably due to the smaller NO_x peaks in the morning hours of the weekend (Schneidemesser et al., 2021).

The Middle East

Researchers observed a slight increase of about 2% in ozone levels during the partial lockdown in Cairo and Alexandria. However, slight reductions in O_3 concentrations were observed in less congested urban areas in Egypt (Mostafa et al., 2021). In Baghdad Iraq, the increase in O_3 was greater than in Egypt. In Baghdad, researchers measured a 13% increase in O_3 concentrations during the first lockdown period compared to the period before the lockdown (Hashim et al., 2021).

Asia

In China, researchers similarly noted that reductions in NO_x levels led to an increase in O_3 levels during the pandemic (Chu et al., 2021; Fan et al., 2020; Le et al., 2020). In India, they came to a similar conclusion, during the lockdown, NO_x levels decreased resulting in an increase in O_3 emissions (Manchanda et al., 2021). For instance, researchers in Mumbai and Delhi measured an overall 2% increase in O_3 levels (Shehzad et al., 2021). According to Singh et al. (2020), there was even an increase of about 20% in O_3 concentrations in Delhi. However, not all researchers agree that O_3 emissions have increased. According to Sathe et al. (2021), O_3 concentrations fell between 22 and 56% during the lockdown period, expected for Kolkata and Delhi. In Kolkata, they measured a 66% increase in O_3 levels and in Delhi they found mixed results. Some stations in Delhi recorded an increase in O_3, while others measured a decrease (Sathe et al., 2021). In East Java (Indonesia), they found no variations in O_3 concentration during the period of social restrictions. However, they did record a decrease in O_3 levels during the restriction period, but this decrease can be explained by cloudy weather conditions and local meteorology (Purwanto et al., 2022).

Particulate matter ($PM_{2.5}$ & PM_{10})

Particulate matter are ultra-fine particles that can consist of elements such as organics, metals, sulphates, nitrates, allergens and dust. The causes of particulate matter can be very diverse. For example, the particles can come from fuel combustion in vehicles or industrial activities. But the particles can also have a natural source, such as dust storms, forest fires or volcanoes. The most common groups of particulate matter are $PM_{2.5}$ and PM_{10} . The subscript of $PM_{2.5}$ and PM_{10} points to the maximum size of the pollutant in micrometres. $PM_{2.5}$ and PM_{10} are quite harmful for humans. PM_{10} can cause cardiac and respiratory diseases if inhaled through the throat, nose or lungs. $PM_{2.5}$, on the other hand, is smaller and can even enter the organs and bloodstream (Albayati et al., 2021).

During the lockdown, researchers observed a decrease in PM2.5. According to Venter et al. (2020), there was a 31% decrease in $PM_{2.5}$. The global level of PM_{10} also decreased (Albayati et al., 2021; Thapliyal et al., 2022). However, the decreases in $PM_{2.5}$ and PM_{10} are short-term effects. From the moment the lockdown measures are relaxed again and economic activities resume, $PM_{2.5}$ and PM_{10} return to their normal pollution levels (Venter et al., 2020).

North America & South America

A decrease in $PM_{2.5}$ and PM_{10} was observed in the United States (Albayati et al., 2021). In California, researchers measured a 31% decrease in $PM_{2.5}$ levels during the lockdown compared to the period just before the lockdown. Compared with previous years during the same period, this decline was 19% sharper than normal (Liu et al., 2021). $PM_{2.5}$ emissions too decreased in Canada. In Toronto, Montreal, Vancouver and Calgary they saw a 6% to 17% drop in $PM_{2.5}$ concentrations. However, the COVID-19 measures had less effect on $PM_{2.5}$ than on NO_2. This is probably because traffic emissions are a major source for NO_2 emissions but a smaller source for $PM_{2.5}$ emissions (Mashayekhi et al., 2021). In Brazil, researchers observed a decrease in PM_{10} levels. The decrease in PM_{10} emissions in Rio de Janeiro was caused by the reduction or the closure of industries, mining and construction companies (Albayati et al., 2021).

Europe

In Europe, the researchers likewise found a decrease in PM_{10} and $PM_{2.5}$. The total emissions change in 2020 was a 3% reduction for PM_{10} and a 2.1% reduction for $PM_{2.5}$ (Guevara et al., 2022). It was also noted in Europe that the reduction in NO_x was much greater than the reduction in PM_{10} or $PM_{2.5}$ (Guevara et al., 2022; Menut et al., 2020). The explanation given by Guevara et al. (2022) for the smaller reduction in PM_{10} and $PM_{2.5}$ is similar to the one given above by Mashayekhi et al. (2021). Guevara et al. (2022) also stated that road transport is the main source for NO_x emissions. However, for $PM_{2.5}$, the main emission source is not road transport, but other combustion activities, such as residential combustion activities. During the lockdowns, residential combustion activities increased slightly, so the decrease in $PM_{2.5}$ is small (Guevara et al., 2022).

According to Guevara et al. (2022), who studied total emission changes in 2020, the largest reduction in $PM_{2.5}$ was measured in Cyprus. A 6.2% reduction was recorded in Cyprus. The largest reduction of 6.5% in PM_{10} was observed in the UK (Guevara et al., 2022). In some parts of Spain and Italy, PM_{10} and $PM_{2.5}$ levels also decreased (Querol et al., 2021; Vultaggio et al., 2020). For example, in the urban area of Palermo in Italy, they measured a 45% decrease in PM_{10} emissions during the lockdown period from 10 March to 30 April 2020 (Vultaggio et al., 2020). In Spain in Madrid, researchers observed a 31% decrease in PM_{10} emissions and a 10% decrease in $PM_{2.5}$ during the lockdown period (Querol et al., 2021). However, increases in PM_{10} and $PM_{2.5}$ were observed in other parts of Italy and Spain. For example, in Bilbao (Spain), $PM_{2.5}$ concentrations increased slightly and in the city of Reggio Emilia (Italy), there was a 27% increase in PM_{10} concentrations and a 31% increase in $PM_{2.5}$ levels (Marinello et al., 2020;, Querol et al., 2021). Marinello et al. (2020) explained the increase in PM in the city of Reggio Emilia by stating that reductions in traffic and industries are not sufficient to reduce PM emissions. PM concentrations also depend on other factors such as meteorology and home heating, which increased during the lockdown period (Marinello et al., 2020). In Krakow (Poland), researchers concluded that the pandemic has no dominant influence on PM10 levels in the atmosphere (Zaręba & Danek, 2022).

The Middle East

In the Middle East and specifically in Jordan, the Emirate of Ajman, Iraq and Pakistan, researchers also observed some changes in PM during the COVID-19 crisis. In Pakistan, they observed a decrease between 15 and 35% in $PM_{2.5}$ concentrations on satellite images. In ground-level observations, $PM_{2.5}$ levels even dropped between 27 and 61% (Khan, 2021). In the Emirate of Ajman, they measured a 40% decrease in $PM_{2.5}$ emissions and a 12% decrease in PM_{10} levels during the 2020 pandemic (Kaied et al., 2021). They also observed decreases in PM concentrations in Jordan and Iraq (Dabbour et al., 2021; Hashim et al., 2021). For example, in Baghdad, Iraq, during the first lockdown, there was a decrease in $PM_{2.5}$ and PM_{10} of 8 and 15%, respectively, compared to the period just before the lockdown (Hashim et al., 2021). We can thus conclude that in the Middle East, PM concentrations decreased during the COVID-19 lockdown.

Asia

In China, researchers too observed a reduction in PM emissions during the restriction period (Fan et al., 2020; Chu et al., 2021). According to Chu et al. (2021), $PM_{2.5}$ concentrations decreased by 35% in Wuhan, where the outbreak started, and $PM_{2.5}$ levels decreased by 19% in the rest of China except the Hubei province, the starting point of the COVID-19 outbreak. In the Guanzhong basin, $PM_{2.5}$ emissions decreased by 37%, while PM_{10} concentrations decreased by 30% (Zhang et al., 2020). Finally, in the River Delta region, researchers observed a decrease in $PM_{2.5}$ concentrations between 27 and 46% during lockdowns (Li et al., 2020).

The researchers similarly found that PM concentrations in India fell during the lockdown. For $PM_{2.5}$ concentrations, decreases between 42 and 60% were recorded. For PM_{10} levels, decreases between 24 and 62% were measured (Sathe et al., 2021). In the northwest and the Indo Gangetic Plain region, the largest reductions of about 50 and 60% in PM emissions were measured (Singh et al., 2020). Overall reductions of 42% and 50% in $PM_{2.5}$ and PM_{10} levels were observed in Delhi and Mumbai, respectively (Shehzad et al., 2021). In the coastal megacity, Chennai, a 66.5% reduction in $PM_{2.5}$ and a 39.5% reduction in PM_{10} was observed (Robin et al., 2021). According to Sathe et al. (2021), the largest reductions in PM were observed in Chennai, Delhi and Bengaluru.

In other parts of Asia, such as South Korea, a 45.45% reduction in $PM_{2.5}$ concentrations and a 35.56% reduction in PM_{10} emissions were observed (Yang et al., 2022). During the lockdown in Malaysia, $PM_{2.5}$ emissions decreased between 23 and 32%, while PM_{10} levels in urban areas decreased between 26 and 31%. In suburban and rural areas, the researchers recorded a smaller drop in PM concentrations. This is probably because these areas are not as affected by anthropogenic pollution (= caused or influenced by humans) (Kanniah et al., 2020).

Oceania

$PM_{2.5}$ emissions did not fall everywhere. In Australia, for example, researchers found an increase in $PM_{2.5}$ concentrations. In Australia, the effect of reduced traffic and economic activity was largely offset by recent forest fires (Venter et al., 2020). However, according to Yang et al. (2022), there was a 10.8% reduction in $PM_{2.5}$ levels during the April 2020 restriction period in Sydney, Australia. In New Zealand, researchers even observed a reduction of 22.6% and 34.1% in $PM_{2.5}$ and PM_{10}, respectively (Yang et al., 2022).

Carbon monoxide and carbon dioxide (CO & CO_2)

CO is a deadly, colourless and odourless gas that can be fatal if inhaled in high concentrations. When inhaled in smaller concentrations, it can damage organs by reacting with oxygen in the blood. CO is formed during incomplete combustion. Sources of CO can be industry or engines, as well as fireplaces, gas stoves and heaters (Albayati et al., 2021). The COVID-19 pandemic reduced global CO_2 and CO levels (Aktar et al., 2021). According to Liu et al. (2020), global CO_2 levels fell by 8.8% in the first half of 2020. Oo and Thin (2022) even suggested a 14.3% decrease in total global CO_2 emissions in the period from January to April 2020. The decline in CO_2 concentrations was driven by reductions in the transport sector, coal-fired power plants and industry (Oo and Thin, 2022). Fossil CO_2 emissions also decreased due to COVID-19 restrictions. Researchers observed a 7% decrease in daily emissions compared to concentrations in 2019 (Quéré et al., 2021). Yang et al. (2022) observed a decrease in global CO concentrations. However, we should keep in mind that reductions in CO_2 levels are only temporary. As the COVID-19 measures were relaxed and economic activities resumed, global CO_2 levels began to rise again (Liu et al., 2020; Quéré et al., 2020).

North America & South America

In the United States of America, researchers measured a 37% decrease in CO levels during the lockdown period (Albayati et al., 2021). However, in California, they observed even a 49% decrease in ground-level CO levels during the lockdown compared to the pre-lockdown period (Liu et al., 2021; Yang et al., 2022). In Peru, a large decrease of 80% was observed during the quarantine period in May compared to March, when there were no quarantine restrictions. In Canada, CO levels decreased by 50% during the quarantine period compared to the year 2018 (Yang et al., 2022).

Europe

In Europe, the total emissions change in 2020 was a reduction of 7.8% for CO_2 from fossil fuels, 4.7% for CO and 3.3% for CO_2 coming from biofuels (Guevara et al., 2022). In Spain (Barcelona), researchers measured a 20% drop during the lockdown period in March and May. In Moscow, they even observed a 38% fall in CO levels and in Lyon (France) a 62% drop (Yang et al., 2022). Changes in CO and CO_2 were also observed in Italy, a country heavily affected by the COVID-19 virus. During the lockdown, car traffic, one of the main sources of CO pollution, decreased. Consequently, reductions in CO concentration were reported. In Palermo, for example, a 51% reduction in CO emissions was recorded (Vultaggio et al., 2020). And in the city of Reggio Emilia (Italy), CO concentration decreased by 22% (Marinello et al., 2020). However, after the lockdown ended, CO began to rise again, reaching levels normal for the time of year (Vultaggio et al., 2020).

The Middle East

As in other parts of the world, decreases in CO_2 and CO levels were also observed in the Middle East during the COVID-19 pandemic. In Morocco, a decrease of 0.04 mg/m^3 was observed in Casablanca (Yang et al., 2022). In the Emirate of Ajman and Jordan, researchers also observed decreases in CO (Dabbour et al., 2021; Kaied et al., 2021). In Egypt, a 5% reduction in CO concentrations was observed in Alexandria and Cairo (Mostafa et al., 2021). Rehmani et al. (2022) also argue that working from home may have reduced your personal carbon footprint if the distance between office and home is greater than six kilometres and you normally use a car to travel to the office.

Asia

Researchers also examined CO and CO_2 concentrations during the lockdown in China. They agree that CO and CO_2 concentrations decreased due to the COVID-19 measurements (Fan et al., 2020; Zheng et al., 2020). According to Zheng et al. (2020), CO_2 emissions decreased by 11.5% during the lockdown period from January to April 2020. A 20% decrease in CO was measured in eastern China and a 33% decrease in the Guanzhong basin (Filonchyk et al., 2020; Zhang et al., 2020). But unfortunately, even these reductions in CO_2 concentrations in China are only short-lived, as the resumption of industrial activities and the economy return CO_2 levels back to the same levels as before the lockdown period (Zheng et al., 2020).

A moderate reduction of 16 to 46% in CO emissions has been observed in India (Sathe et al., 2021). According to Singh et al. (2020), the largest decrease in CO levels during lockdown was observed in India's Ganges Plain region. In Delhi, CO levels decreased by 31.61% during lockdown compared to before lockdown. In Mumbai, researchers even measured a 61.58% drop (Shehzad et al., 2021). The coastal megacity of Chennai showed a 29% decrease in pollution in the urban area (Robin et al., 2021).

They too found reductions in CO concentrations in other parts of Asia. In South Korea, for example, CO emissions fell by 17.33% during the lockdown period in March 2020 (Yang et al., 2022). A 25-31% reduction in CO levels was observed in urban areas of Malaysia. However, no significant reductions were observed in rural areas (Kanniah et al., 2020). In West Singapore, researchers also studied carbon emissions from maritime traffic during the 2020 lockdown period. They concluded that carbon emissions from bulk carriers, container ships, tankers and tugs increased during the lockdown. However, emissions from ferries, general cargo ships, passenger ships and ro-ro ships decreased. This can be explained by the fact that non-essential trips were restricted during the lockdown period in 2020 (Yang et al., 2022).

Oceania

In New Zealand, researchers studied carbon emission reductions from aircraft travel restrictions. Carbon emissions fell from 250 000 kgCO_2-eq in August 2019 to around zero in April 2020. However, this was only a short-term reduction, as emissions went up again to 50 000 kgCO_2-eq in July 2020 (Yang et al., 2022).

Waste

During the covid pandemic, people tried to protect themselves with mouth caps, disposable gloves and disinfected wipes. All these products were often made of single-use plastic. This section looks at the impact the corona crisis had on the amount of waste and also how people dealt with the disposal of this new extra amount of waste. Moreover, the corona crisis also forced people to stay at home because their workplaces were closed or they were not allowed to leave their homes. This created great uncertainty for everyone and led to large quantities of food being bought in panic especially at the beginning of the pandemic. Did this lead to more food waste?

Household food waste

During the COVID-19 outbreak, our food choice behaviour changed. There were concerns that our amount of food waste would increase and that this would increase pressure on waste management systems. Iranmanesh et al. (2022) and Scacchi et al. (2021) both investigated whether our amount of household food waste changed. They both concluded that household food waste decreased in most countries. Scacchi et al. (2021) found a 53.7% reduction in household food waste in Italy. COVID-19 changed our behaviour regarding food. The restrictions, risk of exposure and long queues at the supermarket discouraged us from going to the supermarket as often as before, so we started shopping online more. But we also made more use of leftovers, meal planning, buying in bulk and stocking up to reduce our trips to the supermarket.

During the COVID-19 lockdown, more time was also spent cooking because there were no other things to do and restaurants were closed (Iranmanesh et al., 2022; Scacchi et al., 2021). The increase in home-cooking was reflected in an increase in Google searches for recipes and an increase in purchases of baking products (Scacchi et al., 2021). Home cooking was an important driver of household food waste reduction. In previous studies, home cooking was often associated with more waste, but during the lockdown, home cooking led to less waste. This is because we became more confident in cooking, were more aware of expiration dates, used more leftovers and cooked more efficiently (Iranmanesh et al., 2022).

The COVID-19 period also had a positive effect on the quality of our diet. Researchers noticed an increase in purchases of fresh vegetables (Scacchi et al., 2021). But the COVID-19 lockdown also gave people time to adopt a diet, which led to less food waste, because when you diet, you reduce unplanned food purchases (Iranmanesh et al., 2022).

Furthermore, the lockdown led to more panic buying. The COVID-19 period was a time of great uncertainty. People were afraid of running out of food, which led to panic buying. Panic buying can lead to supply shortages, price inflation and food waste. However, most studies found a non-significant relationship between panic buying and household food waste. This non-significant relationship is probably caused by the fact that we had higher food consumption, used more leftovers and had better shopping plans and stock management (Iranmanesh et al., 2022; Scacchi et al., 2021).

Finally, COVID-19 also had an impact on impulse buying. Supermarket opening hours were reduced, which may lead to pressure to shop quickly. However, in Scacchi et al.'s (2021) study in Italy, they saw that the incidence of impulse purchases was halved. This is probably due to the Italian government's advice to buy only necessary goods, which increased the use of shopping lists. COVID-19 also provided job insecurity, which reduced unnecessary purchases (Scacchi et al., 2021). In contrast, Iranmanesh et al. (2022) suggest that impulse purchases may have increased due to food-related advertising from social media platforms.

Aldaco at el. (2020) does not fully agree with Iranmanesh et al. (2022) and Scacchi et al. (2021). They investigated the change in food loss and waste during the COVID-19 outbreak in Spain. Household food loss and waste increased by 12% during the COVID-19 period. However, when they took into account the rise in consumption, food loss and waste remained similar to before COVID-19. So according to Aldaco et al. (2020), the total amount of food waste did not change, there was only a partial shift to households.

Solid waste

Not only was the amount of household food waste affected by the COVID-19 crisis, the crisis also had a huge impact on plastic waste. Single-use plastic was used in large quantities to protect us from the SARS-CoV-2 virus. The demand for latex gloves, face masks, disinfectant wipes, hand sanitisers, detergents, water bottles and packaged fruits and vegetables increased. Personal protective equipment such as gloves and surgical face masks were usually discarded after one day. This led to a huge increase in plastic waste. Due to the outbreak, 1.6 million tonnes of plastic per day was generated (Benson et al., 2021a; Oo & Thin, 2022).

Benson et al. (2021a) estimated that about 3.4 billion face masks and face shields were discarded daily. An estimated 1.8 billion, 445 million, 411 million, 380 million, 244 million and 22 million were discarded daily in Asia, Europe, Africa, Latin America and the Caribbean, North America and Oceania, respectively (Benson et al., 2021a; Benson et al., 2021b; Oo & Thin, 2022). According to Benson et al. (2021b), about 12 billion face masks were thrown away every month in African countries, with 105,000 tonnes entering the environment. Of the 57 African countries, 15 were major contributors to single-use plastic waste. The six biggest plastic polluters in descending order are Nigeria, Ethiopia, Egypt, DR Congo, Tanzania and South Africa. All these six countries have fairly extensive coastal areas, so if their waste management is not on point, a lot of plastic ends up in the ocean and on beaches (Benson et al. 2021b).

Ammendolia et al. (2021) surveyed COVID-19 waste in the metropolis of Toronto, Canada. They found a total of 1306 personal protective equipment items, of which 31% were face masks. 95% of the face masks were surgical face masks, only 3% were reusable masks and 2% were dust masks. Most face masks were discarded in the hospital district. This is probably because you had to cover your face before entering the hospital (Ammendolia et al. 2021). If face masks are not disposed of properly, they can break down into microplastics and cause a lot of damage to the environment. Surgical face masks are made of polymeric materials. Polymeric materials are one of the causes of pollution by microplastics. Under different environmental conditions, such as temperature and humidity, face masks disintegrate into small particles less than 5 mm in size. These tiny particles end up in the environment and in all water sources around the world. When microplastics break down, toxic chemicals are released into the environment. Moreover, the fish we consume also swallow the microplastics and microplastics can cause drought. In short, the increase of microplastics in the environment raises concerns about the overall ecosystem and human and animal health (Aragaw, 2020).

Surgical face masks were not the only personal protective equipment used. During the COVID-19 outbreak, there was also a large increase in disposable gloves and disinfectant wipes. 44% of the COVID-19 waste found in Toronto consisted of disposable gloves and 25% of disinfectant wipes. Disinfecting wipes were mostly found at medium-sized grocery shops. Gloves, on the other hand, were mostly found in car parks of large grocery shops. The large amount of glove waste is rather surprising as wearing disposable gloves was not mandatory. Probably, people wore gloves because they were easily available and gave a false sense of protection (Ammendolia et al., 2021). Gloves, like face masks, can be dangerous for marine animals. If they accidentally eat the gloves, it could lead to their death (Benson et al., 2021a).

As mentioned earlier, household food waste decreased during the COVID-19 lockdown, but household waste increased. This is due to high online purchases and home deliveries during the corona pandemic (Shakil et al., 2020). In Egypt, they estimated a 940% increase in online shopping (Mostafa et al., 2021). The increase in online shopping led to an increase in packaging materials, such as thin films, foam and multi-layered plastic (Oo & Thin, 2022; Vanapalli et al., 2021). In Regina, Canada, they also observed an increase in private waste disposal. They explain this increase in waste by suggesting that people have made some home renovations to make working from home easier (Richter et al., 2021). However, the increase in household waste was not observed in every city. In Shanghai (China), for example, a 23% decrease in household waste was observed (Fan et al., 2021). And in Milan, during the strict lockdown, they saw a 20% reduction in paper and cardboard waste and a 16.7% drop in glass waste (Sarkodie & Owusu, 2021). In addition, medical waste increased sharply. In Egypt, they estimated a 30%-50% increase in contaminated medical waste (Mostafa et al., 2021). In Brazil, they observed a two-fold increase in medical waste and in Wuhan, China, even a six-fold increase in medical waste was estimated (Urban & Nakada, 2021).

Waste management

The increase in plastic and contaminated waste put enormous pressure on waste management systems, and if the waste was not handled properly, it could cause a lot of damage to the environment. Moreover, there was a possibility that the waste was contaminated with the SaRS-COV-2 virus and consequently infected other people. Therefore, contaminated waste should be handled with extreme care.

The COVID-19 pandemic had quite an impact on our waste management systems. COVID-19 caused changes in: waste quantity, waste composition, disposal rate and time/frequency, safety and infection risk and waste distribution (increase and decrease at different locations). All these changes brought challenges for the waste management systems. For instance, increased infection risk led to the demand for safety measures (Fan et al., 2021). Municipal solid waste collectors and workers were exposed to contaminated waste on a daily basis. Therefore, it was very important for waste collectors to wear appropriate personal protective equipment, otherwise the spread of COVID-19 would be accelerated (Das et al., 2021a).

Moreover, COVID-19 jeopardised the circular economy of refrain, reuse and recycling. Recycling could expose personnel to coronavirus (Fan et al., 2021). Means of addressing the increase in medical waste were incineration, chemical disinfection and physical disinfection. However, incineration of waste is not really environmentally friendly as it releases certain gases (Elsaid et al., 2021). But immediate recycling of medical waste was also not an option because the SARS-CoV-2 virus is detectable on materials such as plastic, metal, glass and stainless steel for quite some time. For example, the virus was detectable on surgical masks for more than 7 days (Fan et al., 2021; Das et al., 2021a; Das et al., 2021b). Researchers therefore proposed different waste management systems to deal with the waste during the COVID-19 crisis.

Das et al. (2021b) developed the following waste management strategy to improve healthcare waste management systems to make them more sustainable and reduce waste going to landfills. The first step in Das et al. (2021b)'s waste management strategy is waste classification and waste segregation. In the segregation step, waste is separated into suitable containers. This step ensures that recyclable waste is effectively separated from other non-hazardous waste to minimise waste. Infectious waste is usually kept in a colour-coded black or transparent bag or in a container with the biohazard symbol. The segregation step can be made more effective by placing containers for general waste next to containers for infectious waste. The next step in this system is to handle the increased healthcare waste by using temporary healthcare waste treatment centres and temporary transport facilities. Alternative technologies can also help with an unpredictable amount of waste. Examples of these alternative technologies are autoclaves, high-temperature incinerators or SF-CO_2 sterilization technology. Sterilwave, an ultra-compact technique, is used to kill the virus on site, so the waste can be handled without risk of infection and consequently treated in the same way as non-infectious waste. The use of autoclaves can also help increase the amount of recyclable waste. Autoclaves expose the contaminated waste to steam at the required temperature and pressure for a certain time to sterilise the waste. Another option to treat the contaminated waste is storage for up to nine days or using disinfectants such as alcohol or sodium hypochlorite. The last option to treat the waste is pyrolysis or incineration (Das et al., 2021b). Pyrolysis is a thermal degradation process in which long polymeric molecules are converted into shorter, less complex molecules under inert or low-oxygen atmospheres, with or without the presence of catalysts (Purnomo et al., 2021). Pyrolysis or combustion can create value-added products, such as incineration ash used in Portland cement (Das et al., 2021b). However, as mentioned, incineration is not really environmentally friendly as it causes CO_2 emissions. Moreover, it requires a lot of fuel to reach a temperature of over 800°C needed to burn the COVID-19-related medical waste. Pyrolysis, on the other hand, is more environmentally friendly as it creates less carbon emission (Purnomo et al., 2021).

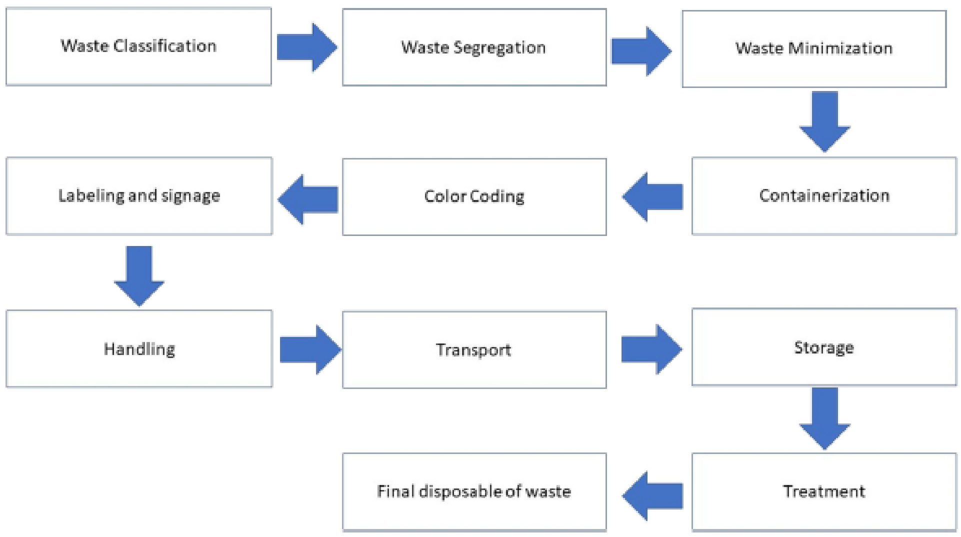

*Figure 2: Overview of healthcare solid waste management during the COVID-19 pandemic (*Das et al., 2021b)

Yang et al. (2020) investigated the management of healthcare waste in Wuhan, China. Like everywhere else, the amount of healthcare waste exploded in Wuhan. The way they dealt with the increased amount of waste was somewhat similar to the waste management system described by Das et al. (2021b). The first step in the waste management system in Wuhan was also to collect and separate infectious and non-infectious waste. The waste was then temporarily stored at or in the hospital. However, during the COVID-19 pandemic, the capacity of the storage sites was not sufficient. It was therefore decided to build 13 additional emergency storage sites. They also increased the number of health waste transport vehicles from 24 to 82. In addition, they also made some adjustments to the treatment facilities. They built a new incineration plant in Wuhan and a steam-based treatment centre in Qianzishan. Furthermore, they provided 34 mobile facilities with different technologies in designated hospitals. The mobile facilities mainly used microwave disinfection, steam disinfection and incineration to process the medical waste. They also started to co-process municipal solid waste and healthcare waste. The most common way to process municipal solid waste and health waste is incineration of waste into energy. Burning medical waste releases gases and ash and it is important to use the right incinerator. Finally, some of the healthcare waste was also transported to nearby cities for non-local treatment (Yang et al., 2020). Thus, we can conclude that Wuhan has made many adjustments to its waste management system to handle all waste without losing sight of sustainability.

Not only did the increasing amount of healthcare waste disrupt waste management systems, but COVID-19 also changed the waste that households threw away. Like hospitals, households were also throwing away contaminated waste. The World Health Organisation gave some guidelines for waste generated during quarantine at home. Tissue paper, face masks and wipes used by infected people had to be deposited in a yellow medical bag, so that it was considered medical waste and not household waste. If the country had a medical waste collection system, they had to treat the sealed rubbish bag and spray the surface with bleach or chlorine. Otherwise, the bag was kept for 72 hours and then incinerated or landfilled (Das et al., 2021a). As mentioned earlier, one of the major concerns in handling contaminated waste was the spread of COVID-19 through waste workers (Vanapalli et al., 2021; Sharma et al., 2020). Thus, it was very important that sanitary workers were protected and trained to handle high-risk biomedical waste (Sharma et al., 2020).

As already mentioned, the corona crisis has also caused a large increase in single-use plastics. Plastic waste is usually mechanically recycled, incinerated or landfilled. However, during the pandemic, mechanical recycling decreased due to lower fuel prices and fear of transmission. The sharp fall in oil prices during COVID-19 caused a dramatic drop in the value of new plastics, reducing the competitiveness of recycled plastics in the market (Vanapalli et al., 2021; Sharma et al., 2020). Moreover, the pandemic tended to exceed incineration capacity due to the increase in packaging and personal protective equipment waste. Incineration is quite common in northern Europe because they have advanced waste-to-energy technologies to process waste without much air pollution. Moreover, the pandemic also caused the overwhelming of landfill capacity due to the huge increase in waste dumped in landfills and the prescription of deep burial for infectious waste. Finally, the pandemic also caused an increase in mismanagement of plastic waste due to inefficiencies and deficiencies in waste management systems (Vanapalli et al., 2021).

The COVID-19 crisis may also have changed consumer perceptions about single-use plastic bags. Local governments promoted plastic bags as protection against COVID-19 infection, and in several US states they temporarily relaxed the ban on single-use plastic. The relaxation of disposable plastic policies may lead to a shift in consumers' sustainable lifestyles. The use of plastic bags is being promoted as normal again, despite evidence that the plastic bag actually prevents COVID-19 transmission. The use and thrown away culture is rekindled among consumers and this may have long-term consequences (Vanapalli et al., 2021; Sharma et al., 2020).

We can conclude that the corona crisis posed quite a few challenges to waste management systems. Therefore, many authors gave recommendations on how to improve waste management during the corona crisis. Not only to make the waste management system more efficient and reduce the spread of the virus through contaminated waste, but also to keep the waste management systems sustainable. For example, Silva et al. (2020 & 2021) suggested using bio-based and biodegradable solutions for food packaging, masks and gloves. Sharma et al. (2020) proposed a national framework for a successful and sustainable healthcare waste management system and the development of new sustainable plastic recycling technologies. Vanapalli et al. (2021) proposed the need for an institutional framework along with directions at the policy level. Both institutional and personal behavioural changes will lead to an inclusive and sustainable plastic waste management system. An example of a social institutional change is investing in research on plastic alternatives. An example of a personal behavioural change is gaining knowledge about the consequences of plastic pollution (Vanapalli et al., 2021).

Water

Not only did air quality and waste management change during COVID-19, but water resources around the world were also affected by COVID-19 measures. In this section, I discuss the pros and cons of the COVID-19 measures on water and I also look at the environment around the water. For example, were the beaches cleaner during the COVID-19 lockdown?

During the lockdown, they really noticed a difference in the Venice Lagoon. In March-April 2020, there was a drastic reduction in water traffic. This mainly because tourism was shut down, but also because commercial boats supplying the city reduced their runs. Lately, the water of Venice's lagoon has become less and less transparent. During COVID-19, however, it was noted that the water became more transparent again. Braga et al. (2020) examined whether this was due to the COVID-19 measures or if there was another explanation for the clearer water. They concluded that the temporary change in water transparency was due to COVID-19 restrictions, but seasonal factors were also influential. For example, the phytoplankton phenology begins its growth cycle in late winter/ early spring, so close to the lockdown period and phytoplankton also leads to high water transparency (Braga et al., 2020). Robin et al. (2021) also found that the clarity of the river Adyar improved during the COVID-19 lockdown.

Jiang et al. (2022), Robin et al. (2021) and Elsaid et al. (2021) all concluded that the water quality improved during the COVID-19 lockdown. Robin et al. (2021) investigated the water quality in Chennai India. They compared the water quality of the river Adyar between pre-lockdown and lockdown and noticed a 47% decrease in the dissolved inorganic nitrogen and a 41% decrease in suspended particulate matter during the COVID-19 lockdown. However, Robin et al. (2021) also observed a small increase in NO_3^--N and a large 128% increase in PO_4^{3-}-P. The large increase in PO_4^{3-}-P may be associated with the intensive use of household detergent during the COVID-19 lockdown (Robin et al., 2021). Not only did the water quality of the Adyar River in India improve, but there was also an improvement in water quality along Lake Vembanad (India) and the Bokhalef River (Morocco) (Elsaid et al, 2021). Jiang et al. (2022) even observed a 0.5°C decrease in mean surface temperature in most coastal regions. According to Elsaid et al. (2021), the groundwater also improved. This was observed in Tuticorin in India. The COVID-19 lockdown caused a decrease in heavy metals such as cadmium, selenium, arsenic, iron and lead. Moreover, the nitrate concentration, total coliform and faecal coliform also reduced by 49%, 52% and 48%, respectively. On the other hand, wastewater quality deteriorated. A higher level of organic load was measured in the wastewater. This higher level is probably caused by the increased use of disinfectants and antibiotics (Elsaid et al., 2021).

Beaches also benefited from COVID-19 restrictions. One of the restrictions was the closure of recreational beaches, which led to cleaner beaches (Jiang et al., 2022; Loizia et al., 2021; Okuku et al., 2021). According to Loizia et al. (2021), who studied the coastal environment in Cyprus, the lack of tourist activity reduced the concentration of micro-, meso- and macroplastics on the beach. Okuku et al. (2021), in turn, investigated the amount of COVID-19 related waste found on beaches in Kenya. They found no COVID-19-related products at most of the recreational beaches because one of the restrictive measures in Kenya was to close the recreational beaches. Depending on whether it was an urban beach or a remote beach, the COVID-19-related waste for the urban beach was between 0.00 and $3.8x10^{-2}$ items m^{-2} and for the remote beach between 0.00 and $5.6x10^{-2}$ items m^{-2}. The higher value at the remote beach is probably due to the differences in compliance with the restrictions (Okuku et al., 2021). The pandemic only temporarily improved the situation on beaches, but as tourism grows, the pressure on beaches will increase. It is therefore essential that authorities develop new strategies to reduce pressure on the coastal environment (Loizia et al., 2021).

Unfortunately, the effect of the COVID-19 restrictions was not all positive. Before the pandemic began, about eight million tonnes of plastic entered the ocean every year. Accumulated plastic can cause great harm to humans, wildlife and their ecosystem. During COVID-19, we all increased the use of single-use plastic by wearing plastic protective equipment or ordering packages online. If handled improperly, plastic waste can end up in the sea and harm the marine environment. Normally, some plastic waste is recycled, but during the COVID-19 crisis, people were afraid of cross-contamination and much plastic was simply burnt or put in a landfill. This is not the right way to handle plastic, so it was estimated that more than 25 000 tonnes of pandemic-related plastic will end up in water (Jiang et al., 2022; Oo and Thin, 2022). For example, China will produce around 702 million wasted facemasks per day and India will produce around 386 million (Oo and Thin, 2022). The big problem with plastic is that it is not resistant to natural degradation processes (Oo and Thin, 2022). Thus, the increase in plastic waste during the COVID-19 period could have long-term negative impacts on coastal waters. Moreover, the pandemic plastic could also break down into nano- and microplastics, leading to irreversible damage to humans and marine organisms (Jiang et al., 2022; Oo and Thin, 2022).

We can therefore conclude that the COVID-19 measures had a number of positive and negative impacts on the water resources around the world. Improved water quality led to more fish and less underwater noise (Jiang et al., 2022; Robin et al., 2021). The reduction in fishing and tourism activities allowed sea turtles to nest again during the day, dolphins were seen in nearby waters and the population of ghost crabs increased (Robin et al., 2021). Moreover, the COVID-19 restrictions also ensured cleaner beaches (Jiang et al., 2022; Loizia et al., 2021; Okuku et al., 2021). However, during the COVID-19 period, there was an increase in plastic waste in the water (Jiang et al, 2022; Oo and Thin, 2022). Furthermore, COVID-19 caused the collapse of marine tourism and the disruption of seafood production (Jiang et al., 2022).

Noise

Noise is a pollutant that does not always get much attention, but can have huge consequences for humans. Noise pollution can lead to anxiety, depression, hypertension, hormonal dysfunction, stroke and cardiovascular disease. Road traffic is one of the sources that cause a lot of noise and, as mentioned, there was much less traffic during the COVID-19 lockdown. But environmental noise can also be caused by commercial, industrial or human activities. During the COVID-19 period, there were many restrictions limiting commercial, industrial or human activities (Basu et al., 2021; Mostafa et al., 2021). Thus, we suspect that noise pollution decreased drastically during the COVID-19 period.

According to Basu et al. (2021), there are four categories of noise. The first category is background noise. This is noise responsible for the buzzing of the peripheral environment. The second category of noise is caused by mechanical equipment such as vehicles. Third, we have noise caused by human activity for example gatherings and household noise and last is environmental noise such as storms and thunderstorms (Basu et al., 2021). During the COVID-19 period, social gatherings were banned and your movements restricted, so we would suspect at least a reduction in the second and third categories of noise. Basu et al. (2021) investigated the changes in sound levels in Dublin, the capital or Ireland. They compared the pre-lockdown situation with the lockdown situation in twelve noise monitoring stations and concluded that noise levels decreased in all twelve monitoring stages. This decrease was probably caused by a decrease in road and air traffic. However, other factors may also have an influence, such as weather (Basu et al., 2021).

Hasegawa and Lau (2022) also examined the change in noise during the COVID-19 pandemic. They conducted a systematic review to investigate the change in noise. The main difference between their study and the study of Basu et al. (2021) is that they also investigated the change in auditory perceptions during the COVID-19 period. Positive perceptual changes included perceptions of an increase in natural sounds and a decrease in traffic noise. More natural sounds lead to a better perception of health and comfort. As mentioned earlier, noise can cause cardiovascular disease, so a reduction in noise improves cardiovascular health. People also said they found the acoustics of their home more pleasant than the acoustics of their workplace. On the other hand, people got the impression that indoor noise increased and noticed the presence of neighbourly noise more (Hasegawa and Lau, 2022). Hasegawa and Lau (2022) also investigated the reduction in noise during the COVID-19 pandemic and they came to the same conclusion as Basu et al. (2021). There was a decrease in noise levels during the COVID-19 lockdown. When the COVID-19 measures became more severe the decrease in noise became greater (Hasegawa and Lau 2022).

Lecocq et al. (2020) investigated the change in seismic noise during the COVID-19 lockdown. Seismic noise is the persistent vibration of the ground due to a multitude of causes. The causes can range from earthquakes to human activity. Lecocq et al. (2020) researched the seismic noise caused by human activity and they recorded the seismic signals on seismometers. They measured the high-frequency seismic ambient noise in 268 seismic stations around the world, in 185 stations there was a reduction in seismic noise during the lockdown. A reduction in seismic noise was observed in more populated areas, near schools and universities and in tourist locations. Lecorq et al. (2020) also concluded that there is a high correlation between pre-lockdown high-frequency seismic ambient noise and audible noise. However, during the lockdown, there was a greater decrease in audible noise than in seismic noise. This suggests that seismometers are sensitive to a wide distribution of seismic sources and not just nearby circulation (Lecocq et al., 2020).

Mostafa et al. (2021) and Shakil et al. (2020) both wrote about environmental noise during the COVID-19 pandemic. As mentioned earlier, there were restrictions on transport, human activity and industrial activity during the lockdown and this resulted in a significant decrease of noise pollution (Mostafa et al., 2021; Shakil et al. 2020). Mostafa et al. (2021) observed a reduction in noise of about 75% in Egypt. Shakil et al. (2020) also found that the COVID-19 led to a significant reduction of noise worldwide. So I think we can safely conclude that the COVID-19 measures had a positive impact on noise pollution. All authors agree that lockdown led to a reduction in noise pollution and consistently to reduction in noise-induced diseases. However, I think it is important to note that after the lockdown all commercial, industrial and human activities returned, so the noise reduction was only a temporary effect.

Discussion

After conducting a systematic review, we can come to several conclusions. First, most measures to control the spread of COVID-19 were quite effective. However, we should not forget that the effectiveness of measures is strongly related to their compliance. Furthermore, a combination of different measures is also more effective in reducing the spread of COVID-19 than one measure alone. Secondly, all the different measures imposed on companies and people also had quite an impact on the environment. Overall, it can be said that most measures had a positive impact on the environment. However, the use of personal protective equipment increased medical waste and plastic in the water.

The content of my thesis is based on 108 papers, so my thesis gives a nice overview of all the research that has been done related to COVID-19 and the environment. However, there are still some limitations regarding the content of my thesis. First, I only discussed the effect of non-pharmaceutical measures on the environment. It might be interesting for the future to also look at the effect of vaccines and PCR tests on the environment. For example, the transport and production of vaccines can also have a significant impact on the environment. Furthermore, in the air quality section, I looked at air quality by continent. However, not many studies have been written on the impact of restrictions on air quality in Oceania. Finally, I only looked at the effect of restrictions on air quality. But for future research, it would also be interesting to look at the opposite question: 'Did poor air quality cause more spread of the COVID-19 virus and thus more deaths?'.

The systematic research carried out in this thesis can provide a source of information to address the current environmental crisis. As mentioned earlier, most measures of COVID-19, which restricted traffic, economic and human activities, improved the environment. However, the improvements were only temporary. If we want to make long-term environmental improvements, we need to make structural changes and develop an action plan (Ibn-Mohammed et al., 2021; Irfan et al., 2021). COVID-19 has damaged the economy considerably. Governments want to fix the economy as soon as possible and are likely to do so through non-environmentally friendly economic growth. However, COVID-19 is the ideal opportunity to start with a clean slate and create a less high-emissions economy (Diesendorf et al., 2020; McElwee et al., 2020). Researchers suggest investing in R&D to develop bioplastic and biodegradable materials. As mentioned earlier, the COVID-19 crisis caused a drop in oil prices, which reduced the value of plastics. The drop in the value of plastics does not make recycling the most economic option. However, it is very important for the environment to create a circular economy in which everything is 100% recyclable by making biodegradable plastics, for example (Giurca et al., 2022). Diesendorf et al. (2020) suggest a recovery/creation of low-carbon, labour intensive jobs lost during COVID-19. One of the environmental problems, for example, is biodiversity loss and land degradation. One possible solution is revegetation with native plants and maintenance of national parks. However, these low-carbon jobs will lead to a growth in economic activity, which consequently leads to an increase in emissions, so low-carbon job creation should go hand in hand with a decrease in consumption (Diesendorf et al., 2020).

The systematic review I conducted has also some limitations. First, I only collected papers written in English, so other languages were excluded from my thesis. Moreover, for my thesis, I only collected papers from the period 2020-2022. No doubt, papers on COVID-19 and the environment will also be written in 2023, but since I conducted my systematic review mainly in 2022, I thought it would be wise to take 2022 as the end date for my research. Furthermore, it was difficult to reduce all the collected papers to a number of papers that I could read. Many people wrote about COVID-19. This is understandable because the pandemic terrorized our lives for more than two years. But the large number of papers made it difficult to collect a number of papers I could handle. However, I did screen all my papers for quality, so normally my thesis only contains papers with a certain level of quality.

Conclusion

COVID-19 turned our world upside down. Governments around the world started introducing regulations to stop the spread of SARS-CoV-2 and reduce pressure on hospitals. All these measures had a major impact not only on people but also on businesses. Many non-essential businesses such as restaurants, bars, offices and schools had to close, and if they were allowed to stay open or reopen, they had to follow certain rules. The restrictive measures discussed in this thesis are: personal protective equipment (PPE), hygiene measures, travel restrictions, closures, contact tracing, staying at home, isolation and quarantine. The effectiveness of each measure is discussed. Overall, we can conclude that all measures discussed were indeed effective in limiting the spread of COVID-19. However, they are most effective when combined with other restrictions. For example, contact tracing is only really effective when combined with quarantine, isolation and/or a travel ban. It should also be noted that some measures, such as contact tracing and travel bans, should be implemented early on a large scale and for a longer period of time. Furthermore, some measures, such as travel restrictions and a stay-at-home policy, are considered very effective but cause quite a lot of economic damage. Stay-at-home policies make people work at home, but in some cases, people such as waiters cannot work at home. Therefore, most countries try to avoid long-term stay-at-home policies. Finally, this thesis also studies the different COVID-19 strategies of different countries. Some countries like China and South Africa and Uganda had quite strict restrictions. While other countries such as Sweden and Tanzania had less strict restrictions.

All these measures introduced by governments had environmental consequences. Some impacts were positive, others negative. My thesis studies the impact of the COVID-19 restrictions on waste, water, noise and air quality. The figure below summarises the positive (+) and negative effects (-) of the measures on the environment.

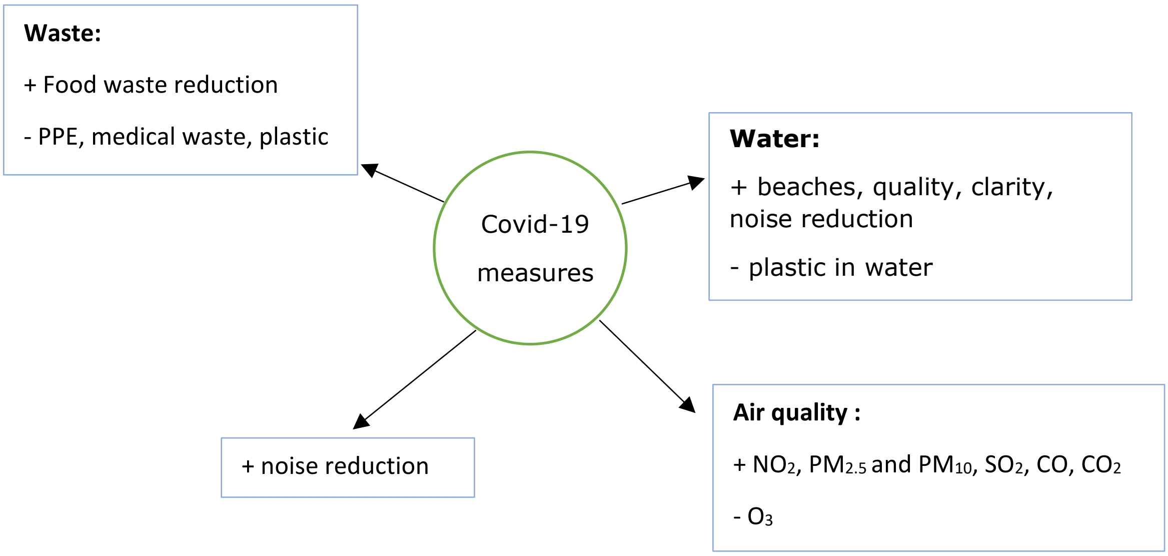

Figure 3: Summary environmental effect of COVID-19 measures

My thesis discusses the impact of COVID-19 constraints on the following elements: SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, CO_2 and O_3. The changes in these elements are discussed separately for each continent. Overall, the COVID-19 measures led to an improvement in air quality due to the reduction in traffic and economic and industrial activities. An global reduction in NO_2, $PM_{2.5}$, PM_{10}, SO_2, CO and CO_2 was observed. However, an increase in SO_2 emissions was observed in some parts of India, such as South India and Mumbai. No changes in SO_2 levels were recorded in the industrial areas of Malaysia as power plants had to remain operational during the lockdown. Furthermore, NO_2 pollution decreased all over the world. The transport sector is one of the major sources of NO_2 pollution. During the lockdown, traffic decreased dramatically, leading to a significant reduction in NO_2 emissions. The greatest reduction in NO_2 emissions was measured mainly in larger cities. However, NO_2 levels were elevated in some parts of India due to fires.

Ozone is the only pollutant that has increased in most parts of the world. The increase in ozone is probably caused by reductions in NO_x concentrations. In some parts of the world, however, ozone levels have decreased or remained the same. For example, in some cities in Spain, India, Egypt and Indonesia, ozone levels decreased or did not change. On the other hand, $PM_{2.5}$ and PM_{10} and CO and CO_2 concentrations decreased during the lockdown period. However, the decrease in NO_2 concentrations was greater than the decrease in $PM_{2.5}$ and PM_{10} emissions in most parts of the world. This is because traffic emissions, which decreased significantly during the shutdown, are a major source of NO_2 emissions but only a minor source of PM emissions. It is also important to note that the reductions in air pollution were only temporary after the lockdowns emissions began to rise again to the same levels as before the COVID-19 pandemic. Finally, some changes in emissions are also partly caused by meteorological factors. Thus, when studying the changes in pollutants during the lockdown, it is very important to consider meteorological data as well.

The COVID-19 restrictions also caused a change not only in the amount of waste, but also in its management. Our amount of household food waste decreased during the COVID-19 period due to more home cooking, use of leftovers, less frequent trips to the supermarket and meal planning. On the other hand, the use of personal protective equipment, such as masks, gloves and decontamination wipes, caused a huge increase in plastic waste. And unfortunately, not all plastic waste was handled properly, so parts ended up in the environment and caused the release of toxic chemicals into the environment and the consumption of microplastics by fish. Moreover, the COVID-19 pandemic also led to an increase in online shopping, which increased packaging material. Finally, medical waste also increased dramatically.

Because of the increase in plastic and contaminated waste, existing waste management systems had to make some adjustments to cope with all the waste, but also to protect the environment and people. Waste collectors were required to wear personal protective equipment to prevent contamination. Moreover, waste was often stored for a certain time until it was COVID-19 free or other alternative technologies, such as autoclaves and pyrolysis, were used to sterilise or dispose of the waste. In China, they even built a new incinerator and emergency storage facilities to handle the increasing amount of waste. The COVID-19 pandemic also caused people to start using plastic bags again, which may have rekindled the throw away culture.

The COVID-19 restrictions had a number of positive and negative impacts on water quality. COVID-19 increased the clarity of water sources around the world. Moreover, researchers discovered an improvement in water quality during the closure, leading to more fish and less underwater noise. Beaches also benefited from the lack of tourism. On the other hand, wastewater quality deteriorated. The use of disinfectants and antibiotics increased the organic load of wastewater. The COVID-19 pandemic also caused an increase of plastic in the water, which will have long-term negative effects on humans and marine organisms.

Finally, the restrictions of COVID-19 led to a reduction in noise, which was mainly due to the reduction in traffic. However, it should be noted that the reduction in noise is only temporary after the lockdown, commercial, industrial and human activities returned and consequently noise levels reached the same level as before.

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