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# The direct emissions related to Global Warming Potential of different types of diagnostic tests at different phases of the COVID pandemic: A climate-focused life-cycle assessment

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## Abstract

The healthcare sector is a major consumer of energy and consumables. This is particularly striking in crisis situations, such as COVID 19, which required the massive deployment of testing and vaccination measures, which have a deleterious effect on the environment. In this paper, we assess the Global Warming Potential (GWP) of COVID19 community testing (aimed at mitigating the spread of the virus) using different diagnostic methods and scenarios. A climate-focused Life Cycle Assessment was conducted to assess the Global Warming Potential of self-testing at home and health worker-performed antigen-based rapid diagnostic tests (RDT), as well as laboratory-based PCR tests. The GWP100 indicator and DALYS were used to compare their respective greenhouse gas emissions and expected health impact. Several scenarios were considered, varying the type of test, transport conditions, and pandemic phase. The expected direct emissions GWP of the tests for the same usage scenario is 0.12, 0.23, 0.69 and 0.73 kg $CO_2$ eq per self-testing RDT, health worker-performed RDT, multiple wells PCR and single PCR respectively. The differences are mainly due to consumables (e.g., protective equipment) and local transport rather than the test itself. The emissions generated by the detection of a true positive is estimated at 1 kg $CO_2$ eq in the high transmission phase of the pandemic, but at 100 and 2.000 kg $CO_2$ eq for RDT and PCR respectively in the low transmission phase. When considering the GWP of COVID tests, RDTs are a better option than PCR in all scenarios. For community testing, this is all the more true as there is no clear health benefit either of using PCR rather than RDT. Our results also highlight the disproportionate impact of systematic testing during low transmission phases, due to the very high number of tests needed to detect true contagious cases. It is time to consider not only efficiency but also environmental criteria when designing public health interventions.

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## Introduction

The COVID 19 crisis has necessitated a massive deployment of tests and vaccination measures, all of which have a deleterious effect on the environment. This situation raises the question of the proportionality of health measures at a time when environmental threats such as climate change, loss of biodiversity and pollution, are already causing millions of deaths worldwide. While there is no doubt that it had a major impact on many aspects of our societies [1], it also had an environmental cost. The latter may have seemed secondary in the early days of the crisis, but it now appears that the environmental impact is an important aspect of the pandemic [2], even if the overall environmental balance sheet is still being debated. In the short term, containment and social distancing measures have led to a massive drop in travel, reducing in particular car traffic and aviation, and thus leading to a sharp decrease in $CO_2$ emissions [3]. The drop in energy demand and production also led to lower emissions of other environmental pollutants, such as particulate matter (PM), nitrogen oxides (NOx) and sulphur dioxide ($SO_2$), at least in the early stages of the pandemic [4].

Looking back over the whole pandemic period, the picture is mixed at best. The drop in emissions was only temporary, and quickly returned to pre-pandemic levels, while long term and indirect effects are still difficult to measure. It has been argued that the crisis has, for example, led to a drop in investment in renewable energies, thus reducing efforts to cut global $CO_2$ emissions for the forthcoming years [5]. In addition, some environmental impacts of the pandemic have also been attributed to the healthcare sector. The latter, which is a major consumer of single-use disposable devices and raw materials through its infrastructure, as well as a major consumer of energy, is known to have a high environmental footprint [6]. It was estimated that in 2019, the healthcare sector was directly and indirectly responsible for 5.2% of the world's carbon dioxide emissions. With a share of 6.6% of carbon dioxide emissions directly attributable to the healthcare system, Switzerland ranks among the top emitters. Along with the USA, Canada, and Australia, it is one of the countries where healthcare-related emissions exceed one ton per person [7].

During the COVID pandemic, healthcare systems underwent considerable changes, with a reduction in prevention activities and elective care, and an increase in intensive care and pandemic control activities, such as testing and vaccination. These developments have led to a massive increase in demand for personal protective equipment (e.g., disinfectants, masks, gloves, disposable gowns) and medical consumables (reagents, test kits, vaccines). These equipment and consumables, which contain many plastics, are polluting and energy-consuming [8].

PPEs and single-use materials, which are mainly manufactured in Asia, have been exported on a massive scale, notably to Europe and North America, raising concerns about their impact on global warming, expressed by the Global Warming Potential (GWP), and the pollution associated with microplastics (MP) and microfibers (MF) [9]. Life cycle assessments (LCA) carried out on community and medical masks used in Europe have highlighted the importance of these impacts. In Switzerland, the potential global warming impact of one month's daily use of a disposable medical mask has been estimated at 0.4 kg $CO_2$ eq. This impact is more than doubled (up to 1 kg $CO_2$ eq) when air transport is required [10]. Similar results were obtained in the UK, where the impact of regular use of disposable medical masks by healthcare staff is estimated at 7.3 kg/year (0.6 kg/month) and 13 kg/year (1 kg/month), for transport by boat and plane respectively [11]. It is estimated that over 10 million masks were released into the environment each month during the crisis due to inadequate disposal practices [12]. The decomposition and wear of medical masks produces MPs and MFs that penetrate terrestrial and aquatic environments, posing a threat to human health and animal species [13].

Most studies have focused on protective equipment and consumables such as disinfectants, masks and gloves, while very few have assessed the GWP of diagnostics and vaccines. To date, we have found only one LCA on diagnostic tests, which focused on Polymerase Chain Reaction tests (PCR) carried out in the context of the pandemic in China [14]. The authors report a GWP of 0.6 kg $CO_2$ eq per test, with the majority of emissions (>80%) attributable to disinfection, waste disposal procedures, and truck transport. This value is higher than that reported for other laboratory tests performed frequently in hospitals: a range of 0.074 to 0.274 g $CO_2$ eq was for instance estimated for blood tests [15].

In this study, we aim to assess the GWP of community testing for COVID-19 (aimed at mitigating the spread of the virus), when using different diagnostic testing methods, and to analyse this impact under several scenarios, based on the pandemic situation prevailing in the canton de Vaud region of Switzerland.

## Method

The impact assessment proposed in this study is based on: (1) the construction of diagnostic testing scenarios in the general population, by varying the testing method used (self-testing at home and health worker-performed testing using an antigen-based RDT, and laboratory-based PCR testing) and the pandemic phase and (2) the analysis of these scenarios looking at midpoint (global warming potential) and endpoint (expected health impact) impact indicators measured through a climate focused Life Cycle Assessment (LCA).

### Observation of the testing procedures

Interviews and visits were conducted in different testing sites to observe all steps of procedure: an ad-hoc centre installed on a University campus (EPFL test centre) and a centre based at a community health facility (Unisanté centre in the neighbourhood of Le Flon in Lausanne) using both RDTs, as well as a microbiological laboratory at a tertiary hospital (Institute of Microbiology at the university Hospital of Lausanne) and a microbiological laboratory and testing centre at a peripheral hospital (Yverdon-les-Bains microbiology laboratory) using both PCR. Additional information on sample transportation and waste autoclaving was collected from a private medical analysis laboratory (Unilabs), and the waste processing centre of a university hospital (CHUV, Lausanne). The visits made enabled us to understand the operating procedures (equipment used, consumables). No personal data on tested individuals or staff was collected.

### Type of testing methods

For testing based on PCR, a sample is first taken by a healthcare worker using a nasopharyngeal swab. The sample is then brought, by various means of transport on various distances, from the collection centre to the laboratory, where the genetic material (RNA) of the virus is amplified and detected by PCR. Several PCR modalities were considered in this study: the immediate analysis of a single sample with an individual cassette (e.g., to obtain a rapid test result), or the accumulation of several patient samples to allow simultaneous testing using 8- to 96-well cassettes.

Antigen-based RDTs for COVID-19 are simple, rapid, and portable lateral-flow cassettes, detecting viral nucleocapsid proteins [16]. Although less sensitive than PCR from an analytical point of view [17], they are cheaper and faster and do not require highly qualified personnel. The result can be visually interpreted by the user a few minutes later. Two testing methods using the RDT were considered, depending on whether they are performed at home by the patient himself or herself (ST-RDT), or by healthcare workers based at a testing centre (HW-RDT).

The PCR climate-focused LCA analysis was based on the kits typically used in the Vaud region in Switzerland. The RDTs for self-testing analysed are those of the brands Roche, AllTest, and Beright. The RDTs performed by health workers are the same, supplemented by the Abbott brand. Depending on the type of test used, the context (e.g., whether performed by healthcare staff or not), and the purpose of testing (isolation of positive patients in an hospital versus identification of contagious people in the community), the expected performance of the testing procedure is not the same. Average performances were used in our simulations for each test category, considering two parameters: their clinical sensitivity, i.e., their ability to correctly identify infected cases (true positives), and their specificity, i.e., their ability to correctly identify non-infected people (true negatives). As no test is perfect, the best methodologies to compare the accuracy of different tests are those performed "in the absence of a gold standard", but this is unfortunately rarely done [18,19]. We therefore decided to use the values provided by a study using such methodology, which also the advantage of having been performed in the same area as the present analysis (Canton de Vaud) [20]. For self-testing with rapid tests, we used a study performed during the same period in a similar setting in Germany with the same brand of test [21]. The latter did however not use an "in the absence of a gold standard" methodology and could therefore not assess specificity; we thus used the value found in the above study comparing PCR and HW-RDT. Sensitivity and specificity of the three tests are shown in Table 1.

During the COVID pandemic, the aim of testing at ambulatory and community levels was not to detect infected persons in order to manage their sickness (as there is no specific treatment to provide in most cases), but to detect contagious individuals, in order to ask them to isolate and thus mitigate the spread of the virus to other individuals. In this context, using viral culture (reflecting infectivity) rather than PCR (reflecting the presence of both viable and non-viable viral nucleic material) would be more appropriate. As very few studies included viral culture, PCR viral load—which is correlated, even if not perfectly, with viral culture results—is often used as a surrogate to reflect infectivity and thus contagiousness. We therefore used the values of the two studies mentioned above using a (rather conservative) PCR threshold of $\geq 10^5$ copies/mL to define a contagious case [22].

## Effectiveness of community testing

Effectiveness of community testing aimed at mitigating viral transmission depends on several other factors, such as the delay to test result (which is the lowest with self-testing at home with a rapid test and the highest with laboratory-based PCR) allowing earlier isolation of contagious individuals. Effectiveness is also highly dependent on the clinical criteria used to test: the broader the criteria (the extreme being to test asymptomatic individuals, a strategy that was not used during the first wave of the pandemic but, in some places, used extensively later in its

**Table 1. Sensitivity and specificity to detect a contagious COVID-19 case (viral load of $\geq 10^5$ copies/mL) for the various types of COVID tests, used in the present study.**

| Parameter | PCR | HW-RDT | ST-RDT |
|---|---|---|---|
| Sensitivity | 97%[1] | 95%[1] | 91%[2] |
| Specificity | 93%[1] | 99%[3] | 99%[3] |

PCR, polymerase chain reaction; HW-RDT, health worker-performed rapid antigen test; ST-RDT, self-testing rapid antigen test.

[1]https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0282150

[2]https://pubmed.ncbi.nlm.nih.gov/34144452

[3]In both studies, sensitivity of RDT was 100%; we however used values of 99% to take into account that perfect specificity does not exist.

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course), the less specific test results are (because the viral load gets lower, and the probability that a positive test is related to an old infection rather than to the present episode increases, especially for PCR that remains positive for weeks to months after infection).

Effectiveness also highly depends on the pre-test probability, i.e., the prevalence of the disease in the population, which varies a lot according to the pandemic phase. This is why, in the present study, three extreme scenarios were considered: testing during the pic (high prevalence), in between (medium prevalence) or during the tail of the pandemic—(low prevalence) as observed in Vaud Region.

## Impact assessment

GWP assessment is based on the LCA methodology where all incoming and outgoing flows are considered for each major stage of the life cycle, i.e., manufacturing (a), transport (b), use (c) and end of life (d).

The sources of data for the climate-focused LCA were the observations and interviews carried out during visits to the testing centres, direct measurements the material used, and bibliographical research the tests components. Finally, when no data was available, assumptions had to be made. The Ecoinvent database (EF v3.0, Ecoinvent, Switzerland) (https://www.ecoinvent.org/database/database.html) and Balance of greenhouse gas emissions from ADEME [23] was used as secondary data to perform the climate-focused LCA analysis. A proprietary Excel tool developed by the authors was used to perform the analysis. The tool's calculation flows were based on the ISO 14040 standard, and the emission factors were taken from the Excel version of the Ecoinvent database. Both midpoint and endpoint impact indicators were considered in this study. The Global Warming Potential (GWP100) [kg $CO_2$ eq], was used as the main midpoint indicator of environmental impact. GWP100 is a comparative index which quantifies the contribution to global warming compared to that of carbon dioxide, expressed in carbon dioxide equivalent, over 100-year period [24]. Disability-adjusted life years (DALYs) was used as endpoint indicator to reflect the burden of disease expected from the environmental impacts of diagnostic testing. DALYS express the number of years of life lost due to premature mortality, due to time lived in states of less than full health, or years of healthy life lost due to disability. The measurement of DALYs is performed following the ReCiPe method. In this method, DALYs are computed according to four health outcomes: respiratory diseases, cancers, other forms of disease and malnutrition. Each health outcome is linked to the relevant midpoint indicators (e.g., particulate matter and ozone formation for the increase in respiratory diseases) using weighting factors [25]. ReCiPe 2016 (version 1.1) was used in this study, considering a global scale context and a 100-year time horizon (hierarchist perspective), consistent with the time scope of GWP100. Besides, measuring DALYs over a longer timeframe (e.g., the egalitarian 500-year perspective) seems inappropriate, given the uncertainties surrounding the long-term health of the population.

The various phases of the life cycle assessment considered in this study are: manufacture, importation, use, and end of life. A general description of the system boundaries of the climate-focused LCA is presented in Fig 1. Detailed system boundaries for the different tests, as well as detailed description of these LCA phases are available in supplementary material (S1 File). The main assumptions and scenarios considered on the basis of our observations and information gathering are as follows (default scenarios):

- Testing systems used in Europe were imported by boat from Asia.
- A typical urban scenario for a 5 km trip was defined for local transportation (included in the use phase).
- Two scenarios for PCR multiple-well test were considered: a full 8 well cassette and a half-full 96 wells cassette.

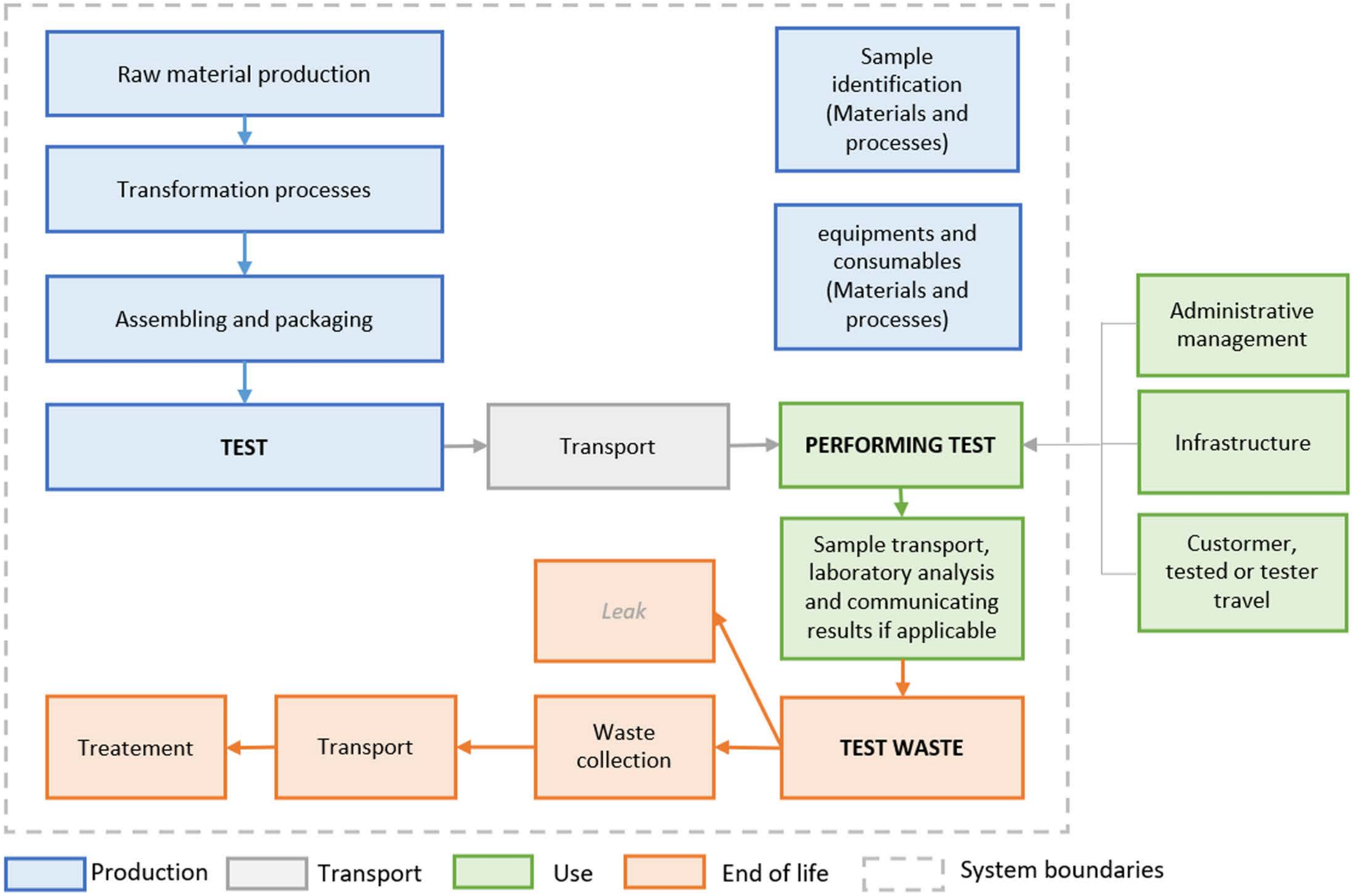


**Fig 1. General illustration of the system boundaries.**

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Results are expressed according to two functional units: (a) the performance of a test, and (b) the detection of a positive case. The latter is used to weight the impact of the test in terms of GWP and DALYs against the expected benefit in terms of public health. As a matter of facts, the effectiveness of testing depends on the identification of positive cases, which helps to slow the spread of the pandemic by isolating contagious individuals.

## Results

Fig 2 shows the estimated impact of direct emissions in GWP terms for different tests typologies under a common use scenario. The scenario considered here is that of tests imported by boat from Asia, a testing frequency of 5 individuals per hour in a care centre (for HW-RDT and PCR tests) and local transportation by car for 5 km. Two situations are considered for the PCR test: that of an individual cassette or that of a multi-well cassette (8-well cassette with 8 samples or 96-well cassette with 48 samples). Only the average results for each test typology are given, with the uncertainty bars representing the variability observed between the different brands and cassette sizes (for PCR with multiple wells cassettes). Detailed results per brand are available in supplementary material (S2 File).

$CO_2$-eq impact of the different tests varies between 0.12 and 0.73 [kg $CO_2$ eq/test]. The differences between brands, mainly due to the materials used (e.g., aluminium sub-packaging),

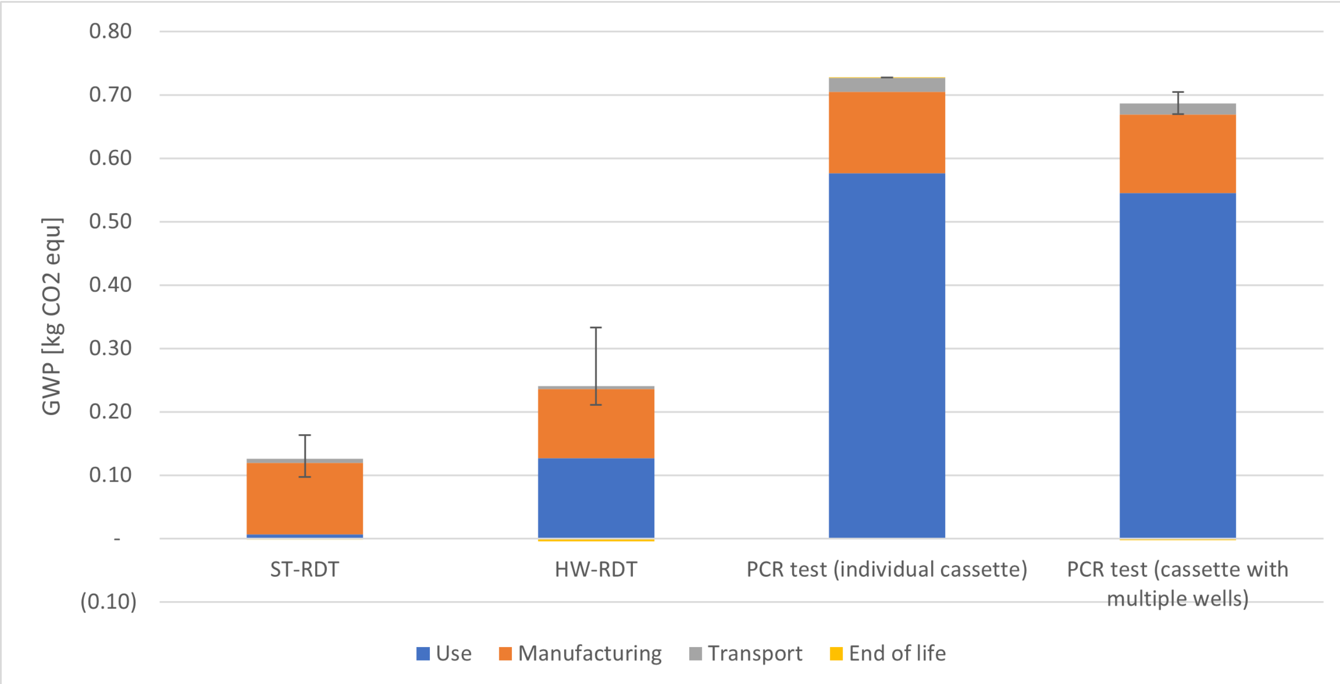


**Fig 2. Average carbon footprint in GWP [kg $CO_2$ eq/test] detailed by life cycle stage and by test.** The vertical bars represent the variation observed between the different brands.

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appears small relative to the differences between typologies. The average manufacturing impact, which lies between 0.11 and 0.13 [kg $CO_2$ eq/test], is similar between the different types of tests. The differences observed in the overall impact of the tests, in proportions of around 1:2:6 for ST-RDT, HW-RDT and PCR, respectively, stem mainly from their implementation (use). PCR and HW-RDT tests, which require the presence of healthcare staff, involve the consumption of disposable protective equipment (gloves, gowns, masks). Moreover, PCR tests require the use of laboratory consumables and equipment, which adds to their overall impact.

## Impact of the local transportation of PCR tests

Unlike the transport of tests from the producer (e.g., importation), the impact of local transport of samples from the test centre to the laboratory (for PCR) is included in the use phase. The default distance of 5 km is that of an average urban journey, in which the PCR sample is transported to the analysis laboratory from a testing centre located in the same town or its outskirts. In practice, local sample transport situations can vary considerably, from a negligible journey when the testing centre is located within walking distance of the laboratory (e.g., a hospital) to a testing centre in a rural or alpine area, which may require transport of several tens of kilometres. Also, some laboratory groups decided to centralise all PCR COVID testing in only one or two of their different sites in the country, lengthening considerably the distance between sampling and testing procedure. The influence of local transport conditions, in absolute and relative terms (% of total PCR test impact) is shown in Fig 3. Detailed information is available in supplementary material (S3 File).

## Impact of the epidemic phase

During an acute pandemic phase, the incidence of COVID cases increases, and more people come for HW-RDT or PCR tests. This trend will be reinforced by the authorities, who tend to

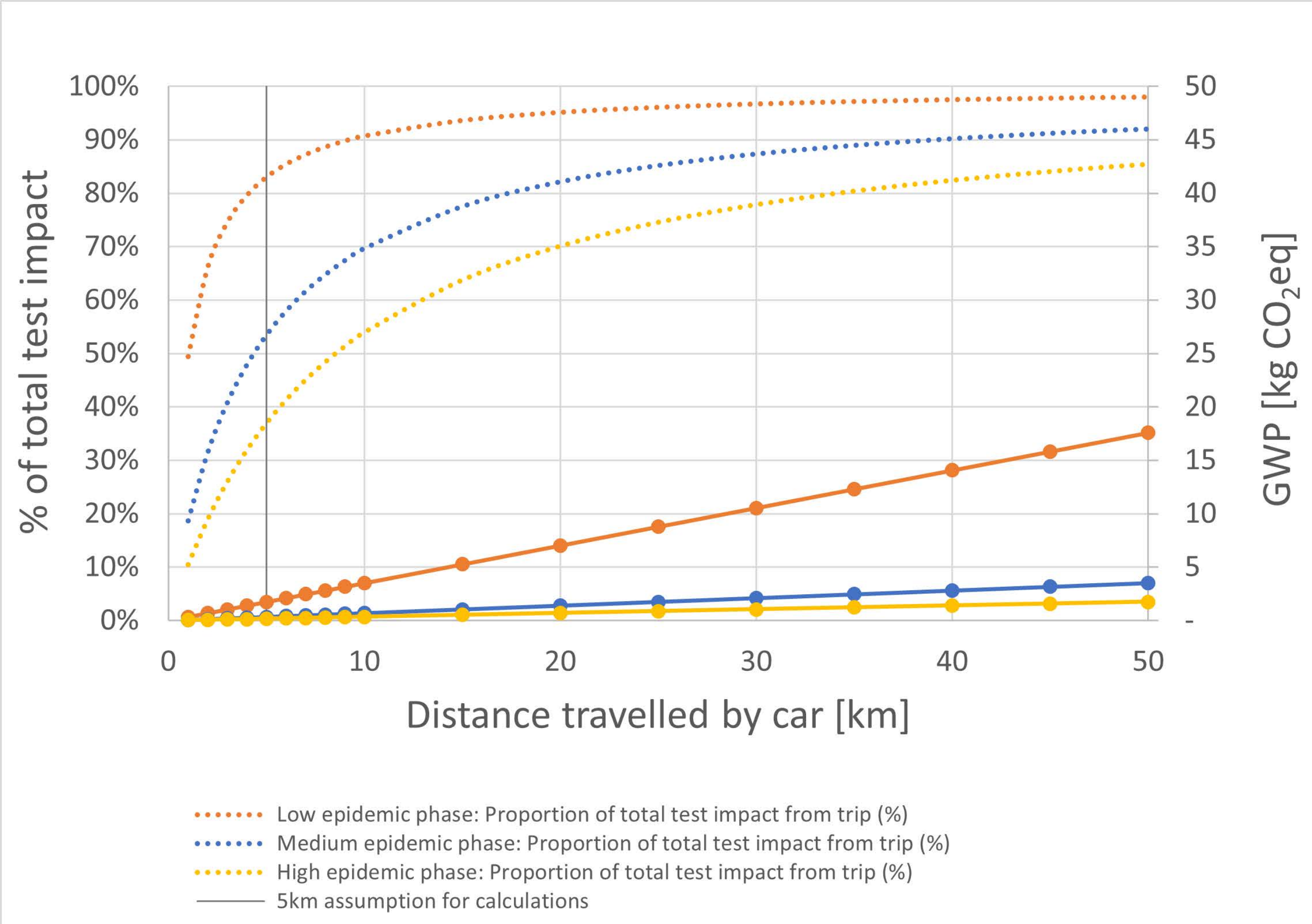


**Fig 3. Relative and absolute carbon footprint in GWP [kg $CO_2$ eq/positive case] of local transportation detailed by pandemic phase.**

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encourage more systematic testing during high pandemic phases. As a result, the rate of testing is increasing (healthcare workers are testing more patients per hour), more tests are being transported in the same vehicles, and larger cassette wells are used (for PCR). Conversely, during low pandemic phases, caregivers will see fewer patients, and vehicles and cassettes will convey less samples, while similar quantities of consumables will be used (e.g., PPE, car fuel, laboratory solvents).

The GWP of direct emissions of a PCR test for three pandemic scenarios is illustrated in Fig 4. The scenario considered here is similar to the previous one (import by boat from Asia, local transport by car over 5 km). The test frequency and number of wells are adjusted according to the pandemic phase, with frequencies of 1, 5 and 10 patients per hour per caregiver, as well as single, 8-wells and half-full 96-wells cassettes, for the low, medium, and high pandemic scenarios, respectively. The results illustrate the importance of economies of scale induced by a higher testing frequency. In the low pandemic phase, the GWP cost of a test is 2 [kg $CO_2$ eq/test], around 4 times higher than in the median pandemic phase. In a high pandemic phase, this drops to 0.35 [kg $CO_2$ eq/test], around 1.5 times less than in the median phase.

The importance of the pandemic phase in GWP of direct emissions can be further illustrated by considering a functional unit based on the detection of positive cases (true positives). Based on the specificity and sensitivity of tests, we can determine the number of tests,

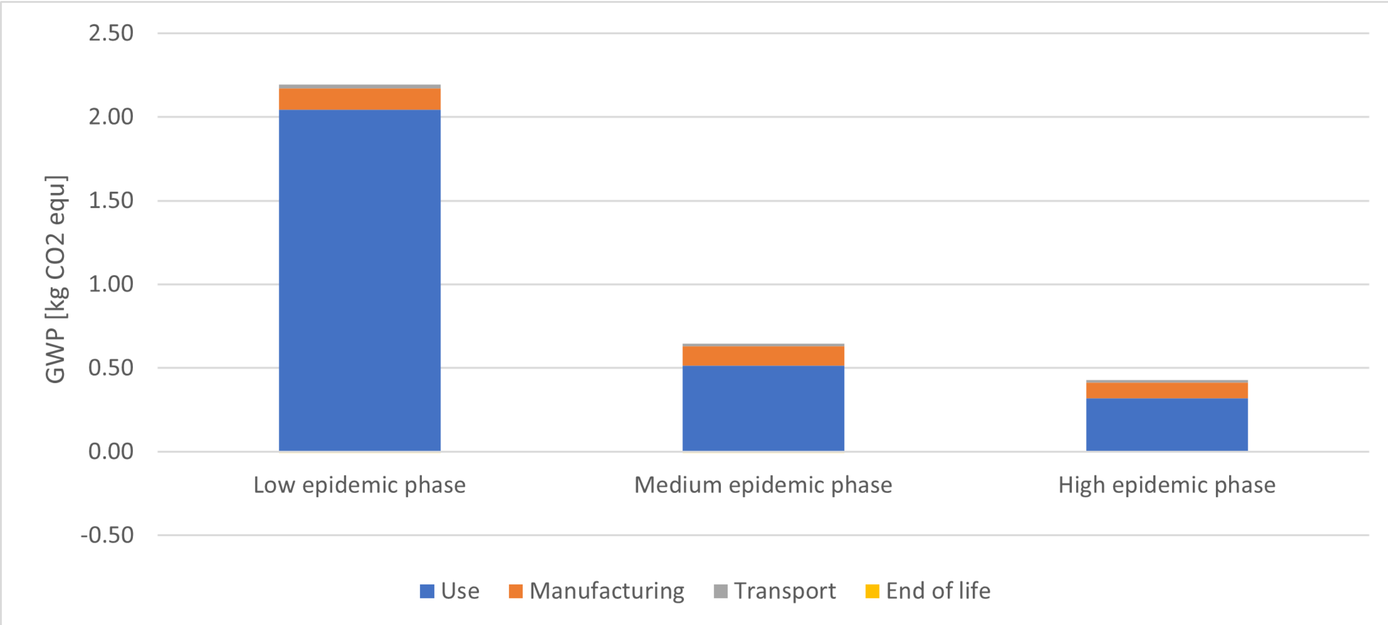


**Fig 4. Average carbon footprint of PCR test in GWP [kg $CO_2$ eq/test] detailed by life cycle stage and by pandemic phase.**

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and therefore their GWP, required to detect a positive case. This impact is illustrated in Fig 5, assuming a prevalence of cases among individuals tested of 1/1000, 1/10 and 1/2, for low, medium and high pandemic phases respectively.

In the same pandemic phase, the impact of ST-RDT is still lower than that of HW-RDT and PCR, despite the lower sensitivity of ST-RDT. As shown on the logarithmic scale of the graph, however, the pandemic phase plays a dominant role in the expected GWP. While the cost of case detection is less than 1 [kg $CO_2$ eq/true positive] in the high pandemic phase, it rises to over 100 [kg $CO_2$ eq/true positive] in the low pandemic phase, with a maximum of over 2,000 [kg $CO_2$ eq/true positive] for PCR. The lower prevalence of cases in the population during the low pandemic phase means that many tests need to be carried out to find a positive case. The correlate of this effect is also that in low pandemic phases, a large proportion of positives cases detected are false positives.

### Health impact

The balance between the expected health benefit, represented here by the detection of a positive case, and the health cost, potentially induced by the environmental impact, is illustrated in Fig 6. Again, the role of the pandemic phase is decisive, with an estimated cost in the order of magnitude of $10^{-3}$ micro-DALYs in the high pandemic phase, and an order of magnitude of 1 micro-DALY in the low pandemic phase.

## Discussion

A progressive increase in GWP was estimated for Self and Health Worker-Testing with a rapid antigenic test, and PCR tests in a proportion of about 1:2:7, respectively. The use phase explains the variations observed between tests, accounting for 40–60% of the impact of HW-RDTs and almost 80% of the impact of PCRs. This is mainly due to the additional medical and laboratory consumables required in the last two tests. ST-RDT have the lowest

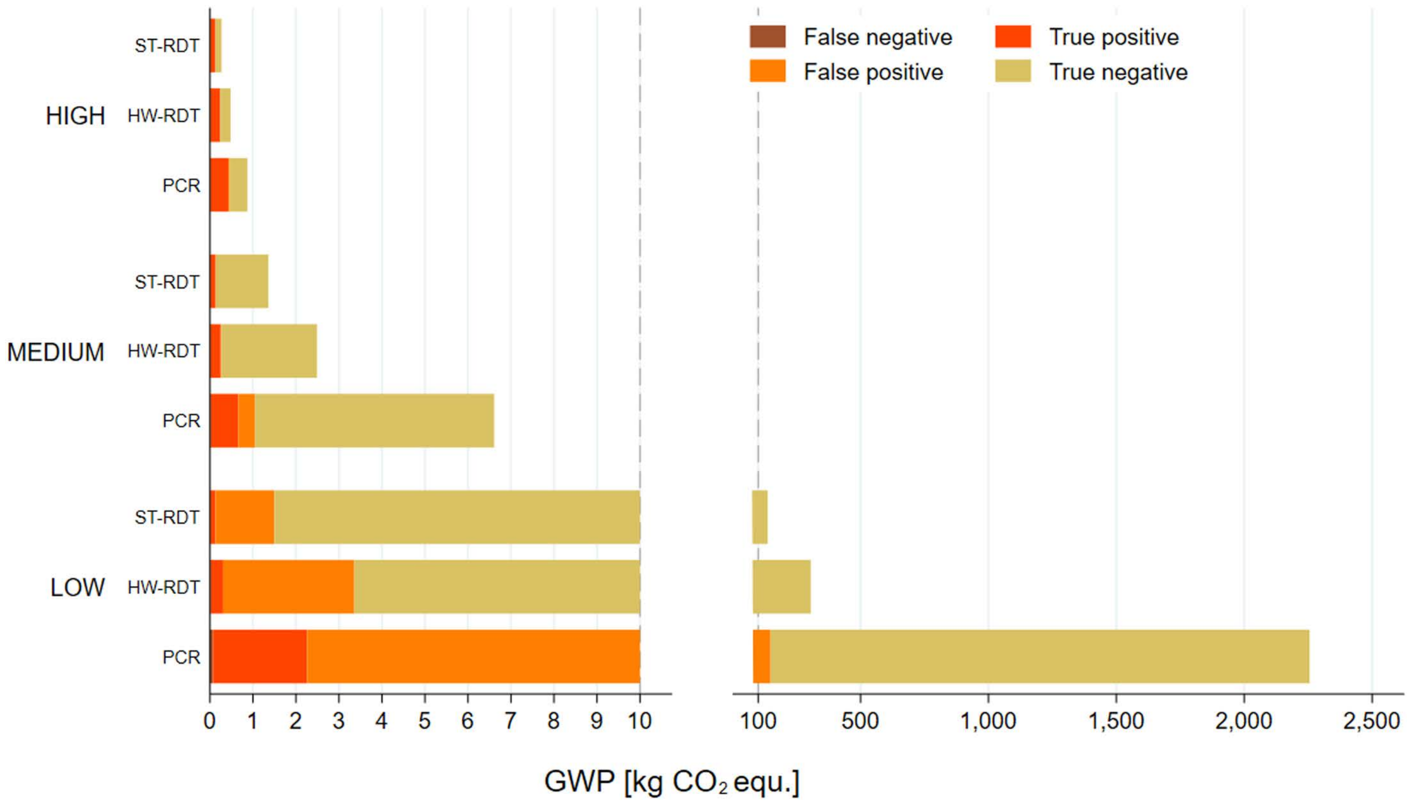


**Fig 5. Average carbon footprint in GWP [kg $CO_2$ eq/positive case] detailed by pandemic phase (high, medium, low) and testing outcome.**

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GWP, but their sensitivity is slightly lower than when performed by a health worker, due to the inexperience of the user.

The GWP of a single test, whether RDT or PCR, remains very low. However, the overall GWP should not be overlooked in view of the considerable number of tests carried out during the COVID pandemic. In Switzerland, during the pandemic (until November 26, 2023), no less than 17.8 million PCR tests and 5.8 million RDTs have been performed, for a total GWP of about 13 700 [t$CO_2$ eq], a value corresponding to the annual $CO_2$ emissions of close to 1'040 people living in Switzerland [26]. Arguably, this GWP remains small in comparison with the overall emissions of the health system. In 2021, the total GWP of testing was of 3'300 [t$CO_2$ eq], which represents 0.1% of the impact of the healthcare system [27].

Various measures can be considered to reduce the impact of these tests. Some design choices, such as metal-free packaging and reduced swab size, could potentially reduce the impact of manufacturing. A number of improvements are also possible in terms of use: (1) The test result communication procedure could be simplified, by sending a weblink to the certificate within the email, rather than as an attachment. The estimated GWP of an email, of 0.004 kg $CO_2$ eq, is indeed around 10 times less than that of an email with attachment [23]. This saving would reduce the GWP by 11 to 14%, depending on the test device. As of July 2022, no less than 600,000 antigenic tests had been performed since the beginning of the pandemic in the canton of Vaud alone. If an action as simple as the removal of the attachment had been practiced for all these tests, more than 18 tons of $CO_2$ eq would have been saved, i.e., more than 32 individual flights from Paris to New-York [28]. (2) Regarding local transportation, it weighs heavily on the impact of PCR tests. Its contribution increases rapidly with

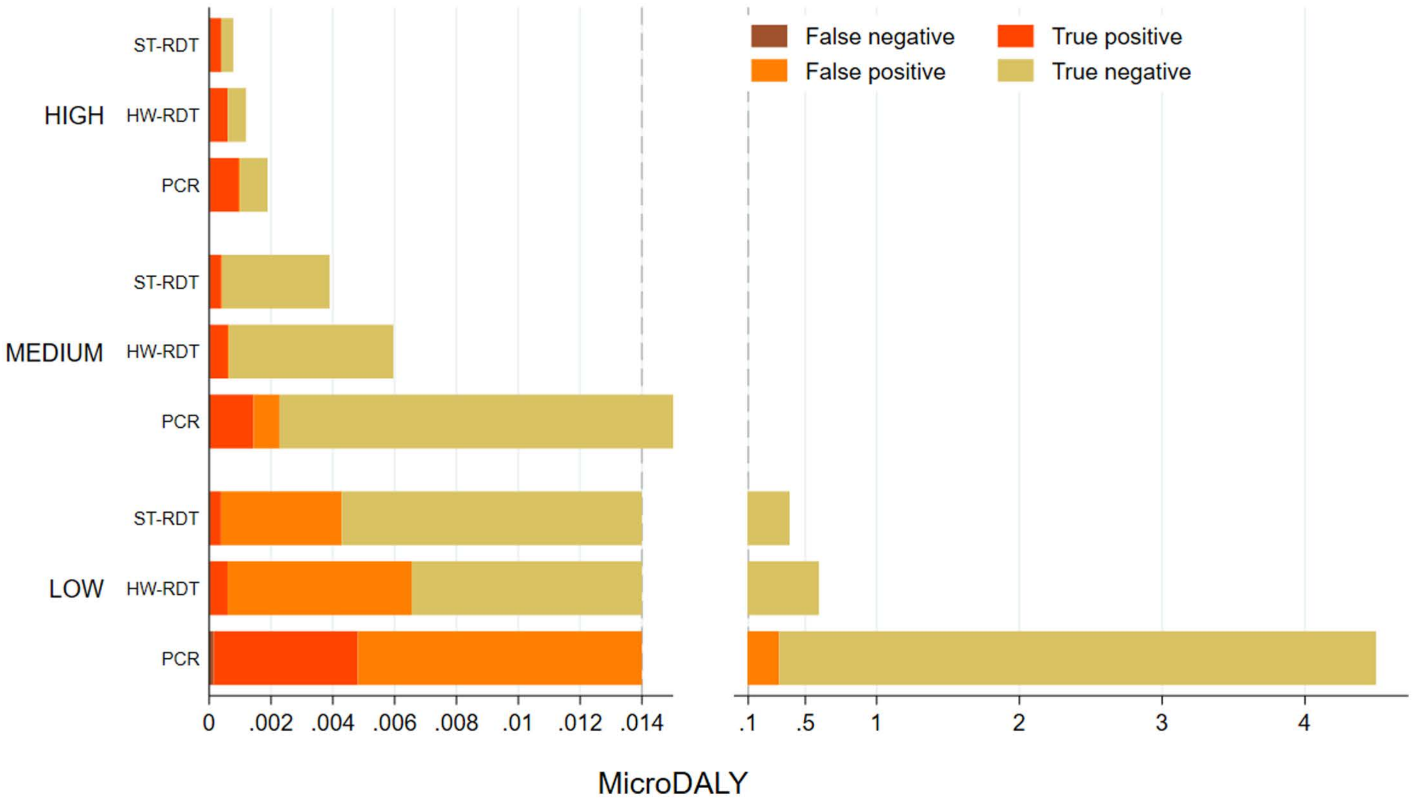


**Fig 6. Average expected health impact in Disability-adjusted life years (DALYs) detailed by pandemic phase (high, medium, low) and testing outcome.**

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the first few kilometres travelled, especially when a low number of samples are transported per trip (e.g., during a low pandemic phase). The use of low impact means of transport (e.g., bicycle courier or train), at least for part of the journey, would make it possible to drastically reduce these impacts. Reducing travel distance of samples by testing centres choosing a laboratory whose site is rather close, whenever possible, could also help. It should be noted that patient transport to the testing site is not within the perimeter of our climate-focused LCA. Given the heterogeneity of situations observed in the field, and the absence of data on patient transport conditions, this process was not included in the analysis, which is a limitation of the study. Including patient transportation would have increased the impact of the tests and increased the GWP gradient observed between the different tests, weighing more heavily on PCR and HW-RDT than on ST-RDT. Since our LCA focuses on direct emissions and does not include indirect emissions such as those induced by patient transportation or the infrastructure required for test production, our impact estimates are likely to be underestimated. The absolute impact of COVID testing, at 0.1% of the Swiss GWP of the whole healthcare system, is modest. In relative terms, the cost of the COVID testing procedure is however high, considering that thousands of different procedures, sometimes with heavy impacts (e.g., MRI) for hundreds of different diseases are routinely conducted in the healthcare system. It should also be noted that the estimates made in this study are conservative.

- Firstly, the time horizon considered for calculating environmental (GWP) and health (DALY) impact is 100 years, which corresponds to a hierarchical cultural perspective. In an egalitarian cultural perspective, represented by a 500-year time horizon, the expected impacts, particularly on human health, are greater. Although the egalitarian model presents more uncertainties, previous studies have estimated that human damage factors are about 5 times higher in the egalitarian model as compared to the hierarchical model [29]. In terms of DALYs, Tang et al. estimated that the egalitarian model led to an impact 9–15 times higher than that obtained from a hierarchical perspective by considering the 2014 WHO risk factors [30].

- Secondly, the scope of the life cycle assessment focused on direct emissions. Data on indirect costs, such as administration or infrastructure, were not available to the authors. In the pandemic context, a wide variety of solutions have been implemented, making it difficult to compare them. This is particularly true for the location of testing centers and the variety of infrastructures, most of which existed prior to COVID, but whose use had been reassigned. Few studies have estimated the indirect impacts of drug or test production in the healthcare sector. Recent publications, however, suggest that the administrative and travel-related impacts on patients are not negligible. Piffoux et al. have estimated that corporate activities are on average responsible for 35% ofCO2 emissions in drug production, with a drop to 10–20% for the least costly and complex drugs [31]. A life-cycle analysis of methylcobalamin supplements carried out in Belgium showed that consumer-related impacts, essentially linked to travel, accounted for 39–44% of the total impact [32].

This specific health intervention highlights the need to take into account these impacts when taking public health decisions. The GWP associated with COVID testing is a good illustration of the imbalance between the impact generated by resource consumption and the expected benefit if environmental issues are not taken into account. The direct benefit of community testing, accounted for in this study, is to be able to slow down the spread of the virus and avoid overloading healthcare facilities in order to maintain the conditions under which individual patients are cared for. In the case of COVID, the expected health benefit is however limited by the fact that some cases are asymptomatic and may continue to spread the disease, despite the detection and isolation of some positive cases. The number of true positive cases detected is used in this study as a surrogate of the direct health benefit of testing. It was indeed not possible to estimate the number of secondary COVID cases adverted, which was previously been estimated to 32% for RDT and 29% for PCR, mainly due to the shorter delay to get the test result [33]. For the present health intervention, the direct health benefit seems thus to favour the same testing method as the indirect (environmental) health benefit. This is however often not the case and there is therefore a need to balance between both types of effects.

Based on the number of true positive cases detected, the expected GWP increases considerably during low transmission phases of the pandemic, with an amplitude of two to three orders of magnitude compared to high transmission phases. A large part of this increase is due to the higher number of false positives, which bring no health benefit and even a societal burden due to all the people who are isolated unnecessarily. For PCR, the GWP of detecting one true positive case during the low transmission phase was found to be of the order of 1 Ton of $CO_2$ eq, and the indirect health of 1 microDALY. These results raise the question of the relevance of large-scale testing during low transmission phases, at least for highly contagious viruses such as SARS-CoV-2 whose transmission can hardly be stopped even with very active contact tracing.

It is important to keep in mind that the scenarios used in this study are relatively straightforward, and that the climate-focused LCA does not take into account the indirect effects of the tests carried out (e.g., the further impact of medical care of false positives). To conclude, these results illustrate the law of diminishing yields applied to testing [34]. The law of diminishing returns postulates that, given the same additional inputs, yields decrease after a certain point. At the extreme, returns can become negative, decreasing profits despite increased inputs. Because of the mass testing strategy applied, COVID-19 testing has followed this trajectory. Intensification is reflected in the increased availability of and access to testing. The greater the supply, the lower the threshold for deciding to be tested and the lower the probability of obtaining a positive result. The extension to broader clinical criteria (up to including asymptomatic individuals), and therefore less specific to COVID-19, as well as the opening and then imposition of mass testing, have in turn decreased the positivity rate of testing, thus increasing the number of tests required to detect a positive case, and even more a true positive one. Finally, the question of the overall health benefit of detecting a case at such costs may also arise in a context of increasing costs. Indeed, each additional 4,434 tons of $CO_2$ emitted into the atmosphere causes (at least) one death in the world [35].

## Conclusion

When considering the GWP of the various type of COVID tests available for community testing, antigen-based RDT, especially when used for self-testing at home, are a far better option than laboratory-based PCR in all scenarios. This is especially true taking into account that, for the specific public health intervention studied here, there is no clear direct health benefit either (nor a financial one) of using PCR.

Our results also highlight the need to adapt testing strategies to the pandemic context to avoid ending up with a very high number of individuals needed to test to be able to detect a truly contagious case. Such an approach would avoid diminishing returns and disproportionate unnecessary GWP.

Overall, the present analysis points to the need, when assessing the impact of health interventions, whatever the type and purpose, to include environmental indicators to be able to weigh up the expected direct health benefits against the indirect health risks due to their GWP.

## Supporting information

**S1 File. Description of the system boundaries and phases of the life cycle analysis.**
(DOCX)

**S2 File. Lifecycle inventory of various tests.**
(DOCX)

**S3 File. Environmental impact of transporting a sample as a function of the number of samples and distance in [kg $CO_2$ eq].**
(DOCX)

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