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Research gaps related to the environmental impacts of electronic cigarettes

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ABSTRACT

Objective To consider the research gaps related to the environmental impacts of electronic cigarettes due to their manufacture, use and disposal.

Methods Literature searches were conducted through December 2013. Studies were included in this review if they related to the environmental impacts of e-cigarettes.

Results Scientific information on the environmental impacts of e-cigarette manufacturing, use and disposal is very limited. No studies formally evaluated the environmental impacts of the manufacturing process or disposal of components, including batteries. Four studies evaluated potential exposure to secondhand e-cigarette aerosol, an indication of impacts on indoor air quality. A 2010 survey of six e-cigarette models found that none of the products provided disposal instructions for spent cartridges containing nicotine. Notably, some e-cigarette manufacturers claim their e-cigarettes are ‘eco-friendly’ or ‘green’, despite the lack of any supporting data or environmental impact studies. Some authors argue that such advertising may boost sales and increase e-cigarette appeal, especially among adolescents.

Conclusions Little is known about the environmental impacts of e-cigarettes, and a number of topics could be further elucidated by additional investigation. These topics include potential environmental impacts related to manufacturing, use and disposal. The environmental impacts of e-cigarette manufacturing will depend upon factory size and the nicotine extracting method used. The environmental impacts of e-cigarette use will include chemical and aerosol exposure in the indoor environment. The environmental impacts of disposal of e-cigarette cartridges (which contain residual nicotine) and disposal of e-cigarettes (which contain batteries) represent yet another environmental concern.

potential that ‘eco-friendly’ claims might be used as a marketing strategy. Accordingly, the environmental impacts of e-cigarettes require further investigation. [Figure 1](#) illustrates the potential environmental impacts of e-cigarettes, including those related to manufacturing, use and disposal; potential environmental impacts and associated research needs are discussed in detail below.

METHODS

Systematic literature searches were conducted through December 2013 to identify research related to e-cigarettes and their environmental impacts. Five reference databases (Web of Knowledge, PubMed, SciFinder, Embase and EBSCOhost) were searched using a set of relevant search terms used singly or in combination. Search terms included the following: ‘electronic nicotine devices’ OR ‘electronic nicotine device’ OR ‘electronic nicotine delivery systems’ OR ‘electronic nicotine delivery system’ OR ‘electronic cigarettes’ OR ‘electronic cigarette’ OR ‘e-cigarettes’ OR ‘e-cigarette’ OR ‘e-cig’ OR ‘e-cigs’ OR ‘environment’ OR ‘environmental impact’ OR ‘nicotine purification’ OR ‘tobacco extraction’ OR ‘indoor air quality’ OR ‘indoor air pollution’.

To be considered for inclusion, the article had to (1) be written in English; (2) be publicly available; (3) be published in a peer-reviewed journal; and (4) deal partly or exclusively with e-cigarettes and their environmental impacts.

The search yielded approximately 170 articles that met the inclusion criteria. Article titles and abstracts (when titles provided insufficient detail) were then screened for relevance. This yielded 18 articles and 3 news releases for full-text review, which included a manual search of the reference lists of selected articles to identify additional relevant publications.

RESULTS

Environmental considerations due to e-cigarette manufacturing

No studies specifically evaluated the environmental impacts of e-cigarette manufacturing; issues related to use of resources, assembly, nicotine source, tobacco cultivation and global production, along with associated research needs, are described below.

Use of resources and energy due to e-cigarette component manufacturing

Although e-cigarette design varies by manufacturers, an e-cigarette generally contains a battery, an atomiser and a cartridge.¹ Typically, the cartridge is wrapped in a plastic bag. Manufacturing the e-cigarette components requires the use of energy and materials; for example, the battery contains metals and heavy metals;

INTRODUCTION

The impact of electronic cigarettes (e-cigarettes) on the public health includes consequences for the environment such as air quality effects, energy and materials used, issues related to environmentally responsible disposal and land use decisions. An environmental impact analysis of e-cigarettes will ensure that regulators, manufacturers and the public are aware of the possible current and future environmental implications associated with the manufacturing, use and disposal of e-cigarettes.

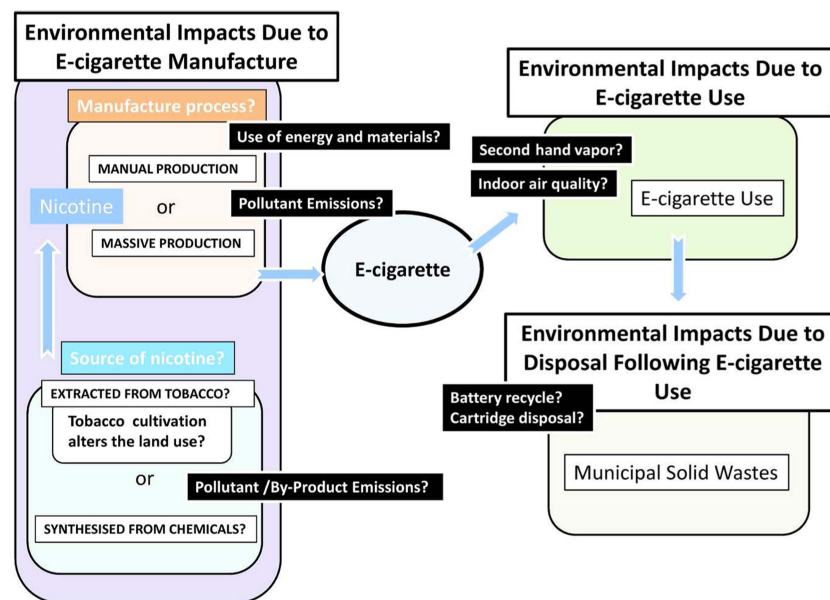
Literature searches were conducted to evaluate the current understanding of the impact of e-cigarettes on the environment. Scientific information on the environmental impacts of e-cigarette manufacturing, use and disposal is very limited. No studies formally evaluated the environmental impacts of the manufacturing process or disposal of components, including batteries; however, there is



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Figure 1 Potential environmental impacts associated with e-cigarettes.



energy-consuming processes are required in order for the metals to be obtained or reclaimed. Furthermore, whether e-cigarettes are classified as 'disposable' or 'non-disposable', the service lifetime of each e-cigarette component is not measured in years but rather in weeks, based on at least one internet posting from a vendor.² Therefore, e-cigarettes are consumable products, just as cigarettes and other tobacco products. It is not clear, for the typical e-cigarette user, how many cigarettes would be equivalent to the use of one e-cigarette. It is also uncertain how the energy and materials used for manufacturing compare if e-cigarettes and traditional cigarettes are evaluated based on consumption: stated alternatively, assuming that a user would consume one e-cigarette to provide a nicotine amount equivalent to 10 traditional cigarettes, it is unclear whether the manufacturing of that one e-cigarette would use less energy and materials than the manufacturing of 10 cigarettes.

Research needs

An analysis that models the use of energy and materials required to manufacture each component of e-cigarettes may reveal whether more or less energy is required to provide the equivalent amount of nicotine compared with traditional cigarettes for an average cigarette user.

E-cigarette assembly

E-cigarettes may be manually assembled in small factories by a handful of employees, or they may be manufactured in assembly lines on a much larger scale. Larger factories will generate greater emissions to the adjacent environment, and therefore will have a greater environmental effect. When an e-cigarette manufacturer meets Toxics Release Inventory (TRI) Program criteria¹ established

by the US Environmental Protection Agency (EPA), it must annually report to EPA its nicotine, lead, ammonia and other pollutant emissions to the water, the land and the air.³ However, EPA does not require facilities that do not meet TRI Program criteria to submit emission information; therefore, individual and cumulative e-cigarette pollutant emission information from all manufacturing sites may not be collectable.

Research needs

Information about the e-cigarette manufacturing process and the size distribution of manufacturing facilities would inform an analysis of the environmental impacts of substances released into the environment during manufacturing.

Source of nicotine

The liquid in e-cigarettes (commonly referred to as 'e-liquid' or 'e-juice') is formulated to contain a mixture of chemicals, including nicotine in some products. Nicotine used for e-cigarettes can be chemically extracted from tobacco plants or tobacco dust.^{4, 5} However, it is not certain if nicotine contained in the e-liquid is formulated using US Pharmacopoeia-grade (USP-grade) nicotine or tobacco extract as the source of nicotine⁶ or if it is synthetic nicotine.

Furthermore, when tobacco extract is used to provide the nicotine content of the e-liquid, the process of extraction generates spent tobacco that potentially contains nicotine and other harmful constituents. It is not clear how the spent tobacco is disposed of or if the spent tobacco is reused for other purposes, such as compost or animal feed.

Purification of USP-grade nicotine from tobacco extract or tobacco dust can be accomplished using aqueous ion exchange, a process that may require a large amount of water⁴; furthermore, a great amount of energy may be used to remove the water. To avoid using a large amount of water, certain anhydrous nicotine purification methods have been developed.⁵ However, these methods use non-aqueous halogenated compounds and generate halogenated waste; such methods may present other environmental issues, particularly the energy used to manufacture the halogenated compounds and disposal of the halogenated compound waste, if it is not properly controlled.

In addition to extracting nicotine from a natural source, scientists have developed methods to chemically synthesise nicotine. For

¹The facility is required to report to the TRI Program if it meets ALL of these three threshold criteria:

- ▶ The facility is included in a TRI-covered North American Industry Classification System (NAICS) code;
- ▶ The facility has 10 or more full-time employee equivalents (ie, a total of 20 000 h or greater; see Code of Federal Regulations, Title 40, Section 372.3), and
- ▶ The facility manufactures (defined to include importing), processes or otherwise uses any Emergency Planning and Community Right-to-Know Act (EPCRA) Section 313 chemical in quantities greater than the established threshold in the course of a calendar year.

example, there is a US patent for a method to chemically synthesise nicotine with the potential for use in industrial production of nicotine.⁷ The chemical synthesis method uses organic solvents including formaldehyde, formic acid and dichloromethane. The intermediate product is purified by high vacuum distillation, which suggests that the waste is emitted to the atmosphere. The final nicotine product is obtained by further reaction with formaldehyde and formic acid, resulting in more emissions to the atmosphere.

It is uncertain which source of nicotine would be selected and which methods would be used by the industry. Nevertheless, the emissions would be substantial in an industrial scale setting if not properly controlled.

Research needs

As nicotine is the key component in e-liquid, the environmental impacts associated with obtaining nicotine would inform an analysis of one of the major environmental impacts of e-cigarettes. An understanding of industrial nicotine manufacturing methods and the associated emissions on an industrial scale is vital in order to evaluate the environmental impacts of e-cigarettes.

Cultivating and harvesting tobacco

As discussed, nicotine can be extracted from tobacco, an agricultural product, and then purified. Assuming that the majority of nicotine used for e-cigarettes is extracted from tobacco plants, the demand for tobacco crops could potentially increase as a result of e-cigarette marketing, which would present a potential alteration in land use. According to a press release from the Wall Street Journal Market Watch, Virginia Tobacco Company, a subsidiary of Universal Corporation, the leading global leaf tobacco supplier, has joined Avoca, one of the world's premier botanical extraction companies, to form AmeriNic, which will produce liquid nicotine for the e-cigarette industry.⁸ At present, no evidence suggests that this merger would result in any increase in the use of tobacco crops.

Research needs

A survey of land area currently used to support production of nicotine and an estimation of the efficiency of nicotine yield from tobacco would assist in identifying the potential land conversion resulting from e-cigarette marketing.

Foreign manufacturing of e-cigarettes and their components

A large proportion of e-cigarettes in the US market are imported; furthermore, certain components and ingredients of domestically produced e-cigarettes are manufactured abroad. For example, purified nicotine might be manufactured in India, while the disposable e-cigarettes might be manufactured in China. A comprehensive environmental analysis requires an understanding of the global impacts due to marketing of imported e-cigarettes or e-cigarette components in the USA.

Research needs

A global analysis of purified nicotine and e-cigarette manufacturing locations would inform an analysis of the environmental impacts of the manufacturing of e-cigarettes that are imported by and sold in the USA.

Environmental considerations due to e-cigarette use

Secondhand aerosol

E-cigarette use is a potential source of chemical and aerosol exposure in the indoor environment. Because the health impact of secondhand aerosol exposure is unknown, WHO has recommended restricting the use of e-cigarettes in public spaces,

similar to that of cigarettes.⁹ E-cigarettes contribute secondhand aerosol to the environment only by emitting particles as they are exhaled by the users (unlike secondhand smoke from conventional cigarettes, which also includes side-stream smoke along with the particles exhaled by smokers).

Four studies have evaluated potential exposure to secondhand e-cigarette aerosol, an indication of impact on indoor air quality.

A series of studies conducted by Schripp *et al*¹⁰ evaluated the potential exposure to secondhand aerosol that can result from e-cigarettes. The studies described by Schripp *et al* evaluated the release of volatile organic compounds (VOCs) and fine/ultrafine particles from e-cigarettes using an 8 m³ emission test chamber. In one experiment, a volunteer was asked to use three different e-liquids (apple flavoured without nicotine, apple flavoured with nicotine, and 'tobacco flavoured' with nicotine) and one conventional cigarette. The air in the chamber was collected before and after e-cigarette use to identify the components released. In a second experiment, VOCs in exhaled breath were measured after a volunteer was asked to exhale one e-cigarette puff into a 10-litre glass chamber. These experimental designs mimic secondhand aerosol exposure. Major components identified in the gas phase included 1,2-propanediol, 1,2,3-propanetriol, diacetyl, flavourings and traces of nicotine. In a third experiment, aerosol was transferred from the e-cigarette into a 10-litre glass chamber using a pump to produce a slight underpressure that then transferred the aerosol directly into the chamber. Measurements were conducted using three types of e-cigarettes, all of which included the same e-liquid. This study showed 'shrinking' of aerosol in a 10-litre glass chamber at 37°C when the aerosol was passed directly from the mouthpiece of an e-cigarette into the glass chamber, instead of being exhaled by the volunteer.

McAuley *et al*¹¹ report on a study conducted using a smoking machine to test VOCs, carbonyls, nicotine, polycyclic aromatic hydrocarbons and tobacco-specific nitrosamines emitted from e-cigarettes in comparison with traditional cigarettes under equivalent experimental conditions. However, the study may present issues of cross-contamination with cigarette smoke, as noted by Burstyn.¹² Furthermore, the experiment was conducted using a smoking machine rather than human exhalation. It is not clear how the exhalation, which is then released to the indoor climate, might affect the aerosol, considering the humidity and air circulation factors that are not present in a study with a smoking machine.

Czogala *et al*¹³ evaluated the release of nicotine, particulate matter with diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}), Carbon Monoxide (CO) and VOCs generated by a smoking machine or exhaled by users in a conventionally ventilated, full-sized room. This room was a 39 m³ emission test chamber equipped with a regulated exhaust ventilation system and two fans for mixing the indoor air. The chamber had plain acrylic painted walls and a tiled floor, with no windows, carpets, linings or curtains inside. The authors used three different models of e-cigarettes selected from the popular brands in Poland and they used two ventilation settings. The air in the chamber was collected before and after e-cigarette use to identify the chemical components released. In one study, the authors used the smoke machine to simulate two scenarios, that of low exposure through secondhand aerosol (with some nicotine absorbed by the user) and high exposure through secondhand aerosol (with no nicotine absorbed by the user). In another study, the volunteers exhaled secondhand aerosol after use in the chamber. Both studies showed that e-cigarettes are a source of secondhand exposure to nicotine but not to CO and VOC, as the

amount of CO emitted was as much as that in the background and only toluene was detected after e-cigarette use. Secondhand exposure to PM_{2.5} was also detected.

Schober *et al*¹⁴ evaluated the release of PM, particle number concentrations, VOCs, polycyclic aromatic hydrocarbons, carbonyls and metals exhaled by e-cigarette users in a ventilated room that contained three tables and a wardrobe (café-like setting) in an office building. The authors used three different e-liquids with or without the addition of nicotine. They found that the e-liquids contained >90% of the humectants 1,2-propanediol and glycerine. They also found that nicotine levels were on average 22% above the manufacturer's declaration of 18 mg/mL, but liquids labelled as nicotine-free had no nicotine present. All e-cigarette solutions contained small amounts of sensitising chemicals including benzyl alcohol, menthol and vanillin. They found none of the tobacco-specific nitrosamines (eg, N-nitrosornicotine, N-nitrosoanatabine, N-nitrosoanabasine and 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone) in the e-liquids. The air in the chamber was collected before and after e-cigarette use to identify the components released. In one study, volunteers exhaled secondhand aerosol sitting around tables in the chamber. That study showed that the amount of PM, 1,2-propanediol, glycerine and nicotine was higher on the vaping days than on the control day. No significant difference was found for formaldehyde, benzene and the pyrolysis products acrolein and acetone when compared with the background concentrations. There was one exception out of the six vaping sessions where the level of formaldehyde was higher than on the control day. Indoor concentrations of the sensitising chemicals vanillin and benzyl alcohol were only slightly increased in comparison with control values. Indoor concentrations of CO and CO₂ showed no difference between control and vaping days.

Research needs

A study evaluating the indoor air quality in other various locations (eg, car, home, office, school and public indoor areas such as transit stations) during and after e-cigarette use would provide important information about environmental impacts. This information should be collected using a representative sample of the e-cigarette products currently available.

Environmental considerations due to disposal following e-cigarette use

No studies have formally evaluated the environmental impacts of the disposal of e-cigarette components, including batteries. However, one study of six products noted that none included disposal instructions.

Disposal of the cartridge containing residual nicotine

Trichounian and Talbot surveyed the design and labelling of six models of e-cigarettes and reported none of them indicated a proper way to dispose of parts of the e-cigarettes, including the cartridge, batteries and atomisers.¹ The authors noted that the amount of e-liquid left in the spent cartridges varied. To estimate the amount of nicotine in 300 puffs from an e-cigarette, Goniewicz found that the amount of nicotine left in the spent cartridges of six e-cigarette brands sold in the UK on the internet varied from 19% to 90% (samples were taken from one to two batches of each brand).¹⁵ When a pharmaceutical product with nicotine as the sole active ingredient (eg, nicotine patches, gum and lozenges) is discarded without being used for its intended purpose, it is classified as a Resource Conservation and Recovery Act (RCRA) hazardous substance.¹⁶ However, a discarded *used* product is not included under RCRA. E-cigarettes

are not a pharmaceutical product; therefore, the disposal of e-cigarettes is not regulated under RCRA or any other programme. This means that the unused and the used cartridges containing residual nicotine can be disposed of without treatment to remove nicotine. Although some manufacturers have initiated recycling programmes for their e-cigarette cartridges, the prevalence of recycling for these cartridges is unknown.

Disposal of e-cigarette batteries

E-cigarettes contain batteries. Some manufacturers have also initiated recycling programmes for their e-cigarette batteries. The prevalence of recycling instructions on disposable e-cigarette packages, as well as how frequently disposable e-cigarettes are recycled, is unknown. Heavy metals may be released if disposable e-cigarettes are disposed of in landfills. Furthermore, if the used disposable e-cigarettes are collected and crushed to reclaim the batteries, without proper treatment nicotine residue will enter the environment.

Research needs

A survey investigating disposal behaviour after use, a model estimating release of heavy metals from e-cigarette disposal and an analysis of the amount of residual nicotine remaining in the cartridge after a typical use would contribute to an environmental impact analysis of e-cigarette disposal.

'Eco-friendly' and 'green' e-cigarettes?

Two news releases reported that one e-cigarette manufacturer claimed that they were certified as 'green' by a membership organisation.^{17 18} Based on information provided by the membership organisation, for a business to be certified as 'green', the business is only required to complete certain organisational assessments, prepare a corporate sustainability vision statement and organise an office team that is responsible for the initiative. It is not clear if the organisational assessment requires that the company record environmental measurements or estimates for their manufacturing procedures, such as any improvement measurement regarding the use of energy and resources, a reduction in number of kilowatts of electricity used, or any reduction in gallons of water used. The membership organisation's website lists the marketing benefits of membership, such as complementary news releases and the ability of member organisations to promote themselves as being 'green'.¹⁹

When products are labelled 'green', the products have a greater potential to sell. A survey of 1305 small businesses nationwide conducted in 2012 revealed a significant increase in sales of 'green' products. For example, organic food sales have increased by 238% in the past 10 years, whereas the non-organic food market has only increased by 33%.²⁰ Similarly, a 'green'-labelled e-cigarette may potentially sell better in the market compared with conventional cigarettes and e-cigarettes that are not labelled as 'green'. Furthermore, Yamin *et al*²¹ noted the potential that adolescents could be misled by 'eco-friendly' e-cigarettes and be tempted to use e-cigarettes.

CONCLUSION

Currently, there is limited information on the environmental impacts of e-cigarette manufacturing, use and disposal. Below are several basic questions that would inform an environmental impact analysis of e-cigarettes:

1. What energy and materials are required to manufacture each component of e-cigarettes? Is more or less energy required to manufacture one e-cigarette when it is compared with the manufacture of the number of conventional cigarettes that

