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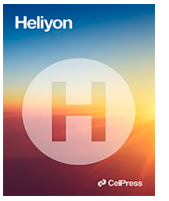

The complex relationship between carbon literacy and pro-environmental actions among engineering students

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ABSTRACT

Lifestyle choices and consumption play a large role in contributing to per capita greenhouse gas emissions. Certain activities, like fossil fuel ground transportation, long-haul flights, diets with animal products and residential heating and cooling contribute significantly to per capita emissions. There is uncertainty around whether literacy about these actions encourages individuals to act pro-environmentally to reduce personal carbon footprints or to prioritize the most effective actions. This study investigated the relationship between carbon literacy and pro-environmental actions performed to reduce greenhouse gas emissions among undergraduate engineering students at the University of Toronto. The pro-environmental actions by the participants produced an average carbon footprint of 4.8 tCO_2 (within the subset of actions included in the survey) which was lower than the average for residents each of Toronto, Ontario, and Canada overall but still higher than the global target of ~2.8 tCO_2e. The carbon literacy by participants was best for high impact actions like ground transportation and dietary choices but less so for air travel and there was mixed awareness for the moderate and low impact actions. For high impact actions and many moderate and low impact actions, participants who thought the action was high impact (even if incorrect) had lower carbon footprints related to the associated activity than those who thought the action was moderate or low impact. The overall relationship between pro-environmental action and carbon literacy was weak. It showed that for high impact actions, there is a slight negative correlation between carbon literacy and personal carbon footprint whereas for moderate and low impact actions, there is a positive correlation.

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1. Introduction

1.1. Background

According to the Intergovernmental Panel on Climate Change (IPCC), global warming should be maintained below 1.5 °C compared to pre-industrial levels to avoid further long-term impacts to the planet and the climate system [1]. To reach this target, global average annual per capita greenhouse gas (GHG) emissions need to be reduced to ~2.8 tCO_2e by 2030 [2]. Implementing low carbon technological innovation on its own will not achieve this ~2.8 tCO_2e per capita target, therefore partnering with individual action to reduce personal consumption is encouraged [3]. There is general agreement that emission reductions (mitigation) must go hand in hand with adaptation to prepare for the changing climate [4–6]. Societal knowledge along with individual behaviour have roles to play in both climate change mitigation and adaptation [7]. This paper contributes to this body of knowledge by focusing specifically on the role of carbon literacy and individual action pertaining to climate change mitigation, while calling for future work to investigate similar relationships between knowledge and adaptation choices.

In Canada, the per capita production of GHG emissions of 14.3 tCO_2e (2021) has been steadily declining but still exceeds the ~2.8 tCO_2e per capita target, is around three times the global average, and consistently ranks within the top ten of countries having more than ten million inhabitants [8], along with the United States and Australia. Compared to the higher emissions from Canada, many countries with similar standards of living have been able to achieve close to the global average, including France, Portugal, and the United Kingdom. In contrast, the countries with the lowest emissions tend to be among the least developed and often face the largest risk from climate change while not contributing significantly to the GHG emissions [9].

Within Canada, Ontario produces the second highest GHG emissions at a provincial/territorial level and emissions in Ontario started rising again in 2018 after steadily decreasing from 2000, notably due to transportation and buildings [10]. Within Ontario, the city of Toronto, which is the most populous in Canada, averages annual per capita consumption GHG emissions between 16 and 21 tCO_2e [11]. While Toronto does not have the highest household per capita GHG emissions in Canada, opportunities nevertheless exist to reduce GHG emissions at the personal level through reduced household consumption [12,13]. Globally, household consumption accounts for about two-thirds of GHG emissions, including direct emissions through personal transportation, energy use within the home and indirect emissions through food [2]. In North America, the personal actions that may contribute significantly to reducing consumption GHG emissions actions are having one fewer child on average, living car-free, avoiding one long-haul flight, eating no meat and managing residential energy use [2,14,15].

While many of these actions are likely to retain substantial mitigation potential for the immediate future, changes in technology may also bring important alterations. For example, the ongoing electrification of passenger vehicles and home heating, coupled with low carbon electricity generation, could substantially reduce (but not eliminate) the GHG benefit from reduced car use or residential energy efficiency. However, emissions reduction depends on the large-scale roll out of these technologies and on the ability to transition to and maintain low carbon electric grids – both of which continue to face challenges. Thus, while electrification is strategically planned by Canada and many countries worldwide, the progress is not fully on track for many technologies [16,17]. Therefore, pro-environmental personal actions are still relevant and necessary for reducing GHG emissions, both as a complement, and also to reduce the required burden for deploying these low carbon technologies.

There are misconceptions about the actions one can take to reduce emissions, in that individuals tend to underestimate the impact of air travel, meat consumption and residential energy management and overemphasize the impacts of actions like recycling and using Light Emitting Diode (LED) bulbs [18–21]. Nevertheless, there are mixed messages regarding whether a lack of knowledge (information deficit) is the reason for not acting pro-environmentally. Some studies show that the information deficit model communication method has not been known to work in modifying behaviour [22–24]. In contrast, recent studies are refreshing the usability of the information deficit model as an effective tool if used inventively [25–27]. In the higher education context, a longitudinal study conducted at San Jose State University (USA), published in 2020, comprising more than 500 university students who participated in a year-long intensive course about global climate change, demonstrated that personal pro-environmental actions persist more than five years after course completion, due in part to what was learnt during the course [28]. Thus, there is evidence that education may facilitate pro-environmental behaviour. Over the last two decades there has been an increase in research regarding green marketing and consumptions patterns [29], although it is unclear whether the findings of these research show a correlation between sustainability knowledge and corresponding actions. Therefore, a deeper understanding of an individual's knowledge about these actions, the relative impact of these actions and their corresponding application of these actions may provide solutions to reduce emissions.

1.2. Research opportunity

Extensive research has been conducted to evaluate climate change knowledge, perceptions and pro-environmental behaviour across a variety of demographic groups that include K-12 students [30–38], the general public [39–49] and post-secondary students [20,50–57]. There is a considerable body of research concentrating on K-12 students and some studies include post-secondary students, but perhaps the fewest studies were conducted on engineering students [21,58,59]. Engineers are the designers and innovators of our built world and understanding their commitment to reducing GHG emissions in their personal lives, that shape and form part of their identity and responsibility to society, has not been sufficiently previously explored. Thus, to devise efforts to curtail GHG emissions, it is important to determine how well the most promising personal GHG emissions reduction actions are understood and carried out by the engineering student demographic at the University of Toronto (UofT) in Canada.

The goals of this study are to discern the carbon literacy (CL) of engineering students at UofT, measure pro-environmental actions

(PEA), determine whether there are correlations between CL and PEA, and identify misconceptions about the GHG impacts of specific individual choices. The study uses Life Cycle Assessment (LCA), a trusted engineering tool to quantify the environmental impacts of products and processes from the cradle to grave.

1.3. Research questions

The study aims to answer the following research questions for undergraduate engineering students at UofT:

RQ1 Are students knowledgeable about the level of impact consumption choices have in reducing GHG emissions?
RQ2 What are the pro-environmental actions of the survey participants?
RQ3 How is knowledge about consumption choices related to participants' pro-environmental actions in reducing GHG emissions?

2. Frameworks

2.1. Carbon literacy (CL)

RQ1 Are students knowledgeable about the level of impact consumption choices have in reducing GHG emissions?

An important first step toward reducing GHG emissions is a person's climate change knowledge/literacy or CL. CL is defined as a person's understanding of the GHG emissions associated with daily activities [60]. A knowledge deficit regarding the actions one can take has been identified as a hindrance to acting pro-environmentally [48,61]. However, the Knowledge Structure Model indicates that declarative knowledge may offer a deeper understanding of pro-environmental behaviour of individuals [62] rather than knowledge deficit alone. The Knowledge Structure Model is a framework to glean insights about the arrangement of an individual's knowledge regarding a specific topic, like sustainability. In this framework, two types of knowledge are presented: declarative (related to facts) and procedural (related to competencies that can transform factual knowledge into actions) [62]. Declarative knowledge comprises system knowledge, action knowledge and effectiveness knowledge. While system knowledge focuses on climate change in general, action and effectiveness knowledge focus on steps one can take to reduce GHG emissions and how impactful those actions are. In this study, the three components of declarative knowledge (system, action and effectiveness knowledge) were measured. However, the action and effectiveness knowledge of declarative knowledge will be explored as these actions are more within the control of the individual.

2.2. Pro-environmental action (PEA)

RQ2 What are the pro-environmental actions of the survey participants?

PEA is defined as an action that causes least harm or benefits the environment [63]. While declarative knowledge may affect one's intent to act, this knowledge may not be the only motivating factor, as purported by the theory of planned behaviour and the mixed messaging from the information deficit model [23–27,64]. There are additional factors, in addition to declarative knowledge, that may also affect whether a person with a certain level of knowledge about environmentally sustainable actions may choose to act upon them. These factors include but are not limited to social norms, barriers, values, and co-benefits [65–72]. Individuals may choose to act pro-environmentally based on social norms, that is, if co-workers or the community are performing an action collectively. It may be that the individual performs this PEA to fit in or out of peer pressure to do so [65]. For example, if the trend within a workplace is switching to a more plant-based diet, one might be more likely to also reduce meat consumption, regardless of the effect of this action to reduce GHG emissions. Individuals may also opt for an action because there are few or no barriers to perform that action [67,68]. For example, if cycling infrastructure exists and the perception is that the activity is safe, individuals may engage in that activity. Social marketing, which aims at socially educating, can augment these activities when there are little to no barriers. Co-benefits refer to additional gains for personal actions, beyond those that aid in climate change and/or reduce GHG emissions [73–76]. Co-benefits examples include: 1. active travel by cycling, running, walking or taking public transport which increases exercise, likely takes place outdoors, facilitates social interaction which in turn promotes greater physical and mental health [74]; 2. household energy efficiency improvement with appliances and better thermal insulation promote better health through improved air quality and provide cost savings; 3. red meat intake reduction which is associated with health benefits like lower risks of colorectal cancer and obesity [77–81].

Past studies that measured PEA among post-secondary students were located predominantly in North America and Asia and tended to focus on ideology surrounding climate change rather than an observational measure or actions where level of impact is considered [18,37,82]. For this study a personal carbon footprint (PCF) is calculated for the participants based on their PEA and the corresponding impacts. There are several existing tools that estimate personal carbon footprint and other emissions associated with climate change mitigation efforts [83–86]. In the present study, we adopt a life cycle assessment approach [87], using a combination of literature values and custom calculations to reflect the life cycle GHG impact of different actions, using locally applicable data where possible. Low PCF is used as a quantitative indicator for high PEA.

2.3. Relationship between CL and PEA

RQ3 How does knowledge about consumption choices correlate to the participants' pro-environmental actions in reducing greenhouse gas emissions?

The relationship between CL and PEA is complicated and one that scholars have tried to measure in the past [82,88–97]. Of these studies, some indicate a positive correlation while others have identified negative or no correlations. This study will explore what type of association exists between CL and PEA/PCF among undergraduate engineering students at UofT and whether their carbon literacy associated with action and effectiveness knowledge play a role in their pro-environmental action choices.

3. Methods

3.1. Survey design and administration

For this study, a survey was used to capture the participants' CL and PEA. The survey for this study was designed by combining and adapting questions from commonly used surveys for measuring environmental knowledge, sustainable choices (carbon footprint calculators), personal values and demographics, as well as independently designed surveys by researchers seeking to investigate specific views. The instrument was evaluated and refined via discussions with experts in the field and tested by respondents with a broad range of backgrounds. The instrument was administered as an online survey comprised of five sections, with a combination of open-ended and closed-ended (nominal, ordinal and continuous variables) questions to give the participants the opportunity to choose among options (closed-ended questions) and express their personal voices (open-ended questions).

Sections 1 and 2 gathered information about participants' personal PEA (section 1) and CL (section 2). The aim was to measure the action and effectiveness knowledge components of declarative knowledge and were based on personal actions one can take to reduce GHG emission. These actions and their effectiveness, defined as high, moderate and low, were identified by a meta-analysis conducted in 2017 [15]. The meta-analysis adopted a LCA approach and calculated the emissions savings per year for individual actions to reduce GHG emissions in developed countries. A subset of these actions and effectiveness are summarized below. As previously discussed in section 1.1, electrification and other ongoing technological developments may alter the relative impact of these actions in future. Nevertheless, the classification below is intended to capture the current reality and the near-term potential for personal action.

High Impact Actions ($>0.8tCO_2e$, >5%/year*)
- Having 1 fewer child in an average family
- Switch from a fossil-fueled car to public transit
- Avoid one long-haul flight.
- Eat a vegan diet.

Moderate Impact Actions ($0.2tCO_2e$ – $0.8tCO_2e$, 1%–5%/year*)
- Wash laundry in cold water instead of hot water
- Recycle fully for one year.
- Air dry clothes instead of using a dryer.
- Waste no extra food for one year.
- Buy only used items instead of new.
- Use only reusable items instead of disposable/single-use items.

Low Impact Actions ($<0.2tCO_2e$, <1%/year*)
- Don't buy GMO (genetically modified organisms) food.
- Replace incandescent or CFL (Compact Fluorescent) bulbs in your home with LEDs (light-emitting diode) bulbs.
- Buy only unpackaged food.
- Buy only local food.
- Turn off the tap while brushing teeth and soaping hands.

*% average North American's annual carbon footprint.

The questions in sections 1 and 2 of the survey mirror each other to enable correlations between knowledge and actions. Detailed PEA information was collected on high impact actions (e.g., dietary choices, transportation distances). For moderate and low impact actions, participants were asked about the frequency, ranging from always to never, in which they actively do certain activities, while the multiple-choice CL questions asked participants to identify if the actions are high, moderate or low impact. Resources used for question selection include carbon footprint calculators from the Environmental Protection Agency (EPA), World Wildlife Fund (WWF), Nature [83–85] and studies seeking answers around individual PEA [15,37,39,46]. The sequence of the questions on the survey was deliberate to diminish certain questions influencing the responses to subsequent questions. For example, PEA was asked first in section 1 before the CL questions in section 2 and open-ended questions were asked before close-ended questions. The survey instrument, information and distribution are in the supplementary information (SI) that accompanies this study (S4, S6).

3.2. Data analysis

A total of 388 responses, including incomplete surveys, were received out of a total enrollment of 5444, as of winter 2021. 364 responses remained after cleaning. Any identifying information provided was removed from the data set. The data was analyzed at an aggregate level without revealing personal identifying information. Any breakdown analysis that resulted in a group size of 10 or fewer participants were either combined with a relevant group or not included in the final reporting due to the risk of the participants being identified.

The main quantitative constructs for the survey are PEA (operationalized via PCF) and CL. These constructs are latent since they cannot be measured or observed directly. The survey captured the constructs using multiple variables in their respective sections: Section 1 for PCF, Section 2 for CL. PCF was calculated for each participant as outlined in Table 1. All emissions calculations were crosschecked with alternate sources and carbon calculators. CL was calculated by summing the scores as follows: if the action was high, medium or low impact and the participant chose the impact correctly, they were given a score of 1. If the action was high impact or low impact and the participant selected low impact or high impact respectively, a score of −1 was given. If the action was medium impact and the participant selected low or high or if the action was high or low impact and the participant selected medium impact, a score of 0 was given. The CL scale was evaluated for reliability using Cronbach's alpha and McDonald's omega, resulting in values of 0.59 and 0.61 respectively. While these values are lower than the recommended minimum of 0.7, psychometricians suggest a lower threshold for exploratory research like this study [98].

Additional details regarding data cleaning/processing, reliability calculations, PCF details and sample calculations and CL scoring and are in SI (S5).

PCF and CL were treated as continuous variables and checked for normality before proceeding. To test for significant differences in PCF and CL, both parametric and non-parametric tests were conducted. Welsch's ANOVA, Kruskal-Wallis was used to test for differences among specific actions and Linear and Loess Regression to determine the relationships between PCF (outcome/dependent) variable and CL (independent variable).

Open-ended questions were thematically coded inductively and independently using Microsoft Excel by the researcher as well as two undergraduate engineering students who were trained on inductive coding methods. After the inductive coding, the researcher and undergraduate engineering students discussed the codes and created a thematic codebook, presented in the SI (S6). The data was then recoded deductively and independently using Nvivo by the same researcher and two graduate students trained in thematic coding using Nvivo. After coding the open-ended responses for the CL and PEA sections, the frequency data was compared to the quantitative responses for CL and PEA respectively. The PEA and CL frequencies were also compared to determine if there were any relationships between them.

4. Study findings

4.1. Demographic information

A breakdown of demographic and departmental affiliations of participants is presented in SI (S5). Of note, the survey included similar numbers of men and women (despite higher enrollment of men in the faculty), somewhat uneven participation across departments, and slight majorities for each of Canadian-born (national origin), not religious/not spiritual (religious identity) and liberal or moderate (political orientation). Implications for sample representativeness will be discussed in Section 5.

Table 1
Summary of Personal Carbon Footprint (PCF) emissions calculation for each type of action.

PCF Category	Description
Ground transportation	Completed for private cars (gasoline, hybrid and battery electric) and public transportation (buses, trains, subway and street cars) using emissions per km travelled and adjusting for passengers who carpooled or changed transportation methods between warmer and cooler weather. No emissions were allocated to active transportation like walking, cycling [99].
Air transportation	Estimated for long-, medium- and short-haul flights and attributed based on number of each type of flight taken [100].
Food	The number of servings of proteins consumed by type (beef/lamb, poultry/pork, seafood, dairy, beans, nuts, soy) per year, multiplied by the emissions per serving of protein type (animal and plant sources) [101–107].
Food waste	Environmental Protection Agency (EPA) Waste Reduction Model (WARM) tool used and based on the weight of food thrown out and whether it was put in the garbage or the compost [108–110].
Home	Space heating and cooling estimated per square meter and multiplied by average area of the dwelling type reported by the participants and adjusted for the number of persons occupying the dwelling and temperatures set above and below the average for warmer and cooler weather [111–116].
Moderate/Low Actions	Moderate and low impact actions (~250 $kgCO_2e$ and ~100$kgCO_2e$ respectively) [15] were allocated based on the Likert scale selection by participants on a spectrum where those "always" performing the action have no emissions allocated and those "never" have 100%.
Upstream and Production	When applicable, emissions were augmented for upstream factors (gasoline for private cars, aviation fuel for air travel, natural gas for space heating) [117] and production (private car manufacturing) [118].

4.2. Carbon literacy (CL)

RQ1 Are students knowledgeable about the level of impact consumption choices have in reducing GHG emissions?

4.2.1. Quantitative CL

For the CL questions, participants were supplied with definitions of high, moderate and low impact actions in general and then asked to rank a series of items as high, moderate or low through a Likert matrix which we then compared to the 'correct' rankings suggested by the literature. The majority/plurality of participants were able to identify having 1 fewer child, switching to public transit and adopting a vegan diet as high impact actions (63%, 73% and 46% respectively) (Fig. 1A). Avoiding long-haul flights were selected as moderate impact by a plurality of participants, although only by a small margin. The moderate and low impact actions result show mixed response accuracy. A plurality of participants selected reusable items instead of disposable and wasting extra food as high impact action rather than moderate impact actions and selected buying local, unpackaged food and switching to LEDs as moderate impact actions rather than low impact actions.

Comparing this study with a similar study involving a survey of 414 undergraduate students at the University of British Columbia (UBC) [46], undergraduate engineering students at UofT show higher average CL for the high impact actions, about the same for the moderate impact actions and lower average for the low impact action compared to the UBC students (Fig. 1B). The UBC sample did not include engineering students. We also compare to a 2021 report by Ipsos that included more than 21,000 participants from 30 markets globally, aged between 16 and 74; participants were given a range of actions to select which would most reduce GHG emissions in wealthier countries. Of the 1001 participants from Canada, 65% were confident they know the personal actions they can take to reduce the impacts of climate change [19]; however, the results revealed misconceptions. Recycling, buying unpackaged food and using reusable items instead of disposable were selected most frequently by participants as the most effective actions while the high impact actions were less frequently selected (Fig. 1C). These results suggest that UofT undergraduate engineering students have a greater awareness or are better at identifying high impact actions compared to the UBC students and general Canadian public but may overemphasize the importance of some moderate and low impact actions.

4.2.2. Qualitative CL

The participants were also asked an open-ended question to provide the three most effective actions individuals can take (in general) to reduce greenhouse gas emissions. This open-ended question was asked before providing the Likert matrix to select the high, moderate, and low impact actions. Thus, while Fig. 1 assessed the participants' ability to identify high impact actions in a structured setting, the open-ended questions provide a more complete picture of which actions they were able to identify without prompting. This allowed us to differentiate between actions the participants know are high impact compared to those that are salient. For the high impact actions, ground transportation and reducing meat consumption were the most frequently provided responses at 250 and 113 respectively. These actions included using active and public transportation, reducing car usage, carpooling and either switching to a plant-based diet or reducing animal products consumption. Very few participants responded air travel or reproduction choices at 29 and < 10 respectively. The actions in the moderate and low impact categories like reusing, recycling, limiting purchases such as fast

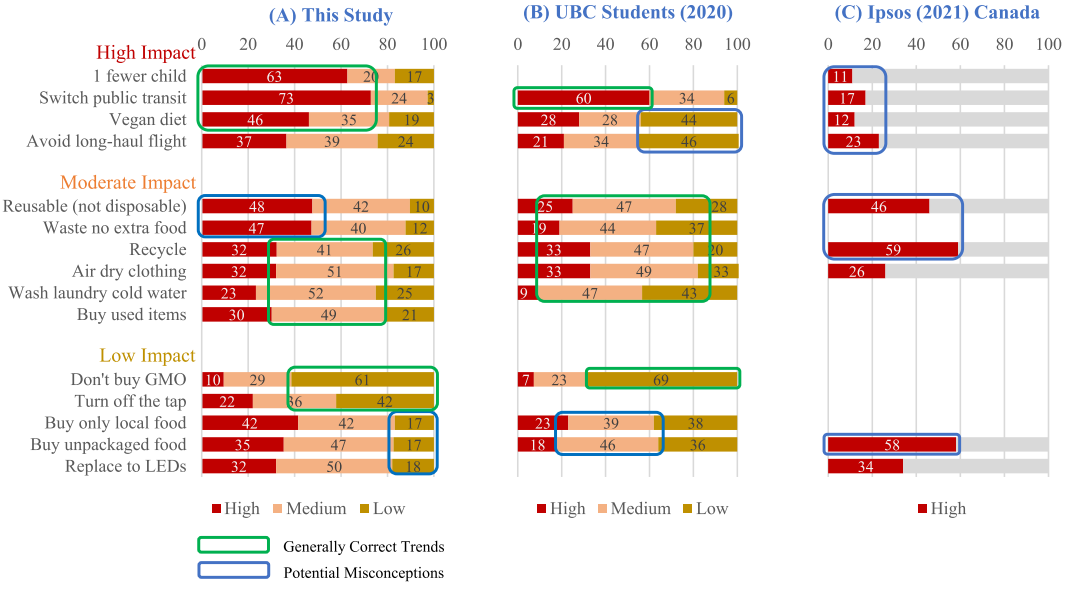

Fig. 1. Ranking of the 15 Carbon Literacy items for UofT participants (panel-A) and comparison with responses from survey conducted by Wynes in 2020 with UBC students (panel-B) and Ipsos 2021 report (panel-C).

fashion, reducing energy/water consumption, and buying local ranged from 75 to 30 responses. Participants also included actions like planting trees or cultivating gardens, shopping from sustainable corporations/brands, industries being major emitters rather than individuals and lobbying or becoming activists. Full frequency tables and example responses are presented in SI (S5).

4.2.3. Quantitative and qualitative CL comparison

Finally, we compare the open-ended responses to how participants subsequently rated each action in the CL Likert matrix. Of the >240 participants who indicated that ground transportation was a high impact action in the open-ended question, 193 subsequently selected it as a high impact action and 51 as moderate impact on the Likert matrix responses (Fig. 2–left). While most participants were consistent in selecting their open-ended responses as a high impact action on the Likert matrix, there are some participants that rated the actions as moderate or low impact. Although most of the participants did not think about air travel or food as a high impact action in their open-ended response, about one third of those did correctly identify them as a high impact action in the Likert matrix (Fig. 2–right). Numbers for low impact are not reported due to <10 participants responding. This suggests a potential dual role for education both to correct misconceptions, but also to ensure high impact actions can be more easily recalled/accessed.

4.3. Pro-environmental actions (PEA), personal carbon footprint (PCF)

RQ2 What are the pro-environmental actions of the survey participants?

4.3.1. Quantitative PEA, PCF

Participants were asked about their pro-environmental actions that are high, moderate and low. The high impact actions included transportation, diet choices and climate control in the home. No questions were asked about reproduction choices. The moderate impact actions included recycling, minimizing food waste, washing clothing in cold water, air-drying clothing, using only reusable items instead of disposable, and buying used instead of new. The low impact actions included buying local with little or no packaging, switching to LED bulbs, turning off lights when not in use and conserving water at home.

For *ground transportation*, participants were asked to select the modes used and report on distances for warmer and cooler weather. In warmer weather, walking and public transit (both under and above ground) were the main forms of transportation with some use of gasoline cars and bicycles. The use of public or active transportation as their main form of transportation aligns with the Student MoveTO survey conducted in 2019 [119]. In cooler weather, walking and bicycle use reduced and gasoline car use increased, although only 26% of participants change their mode of transportation in cooler weather.

For *air travel*, long-haul flights were taken by most of the participants followed by taking no flights, then medium haul flights and finally short haul flights. When asked if they would consider non-aviation modes, almost 90% of the participants answered that was not a consideration.

For *dietary choices*, 86% adopted an omnivorous diet, 12% a vegetarian diet and 2% a vegan diet. For omnivorous diets, dairy ranked highest as often consumed, followed by poultry, then beef and finally seafood which was consumed occasionally.

For *climate control in the home* (HVAC – heating, ventilation and air conditioning), close to 80% had cooling, more than 95% had heating in their homes and 81% had thermostats with 67% of them being programmable. On cooler days, participants generally set the thermostat to lower temperatures when away from home. Conversely, on warmer days, participants generally set their thermostats to higher temperatures when away from home.

Turning to *moderate and low impact actions*, almost 60% reported wasting less than 10% food and of the food thrown out and more than 50% of the participants composted the food waste. Certain Moderate and Low Impact Actions were performed “always” or “often” like recycling, turning off tap while brushing teeth/soaping hands and switching to LED bulbs, while others were “never” or “seldom” practiced regularly like air drying clothes, buying only used items and buying only local food. All PEA descriptive statistics tables and

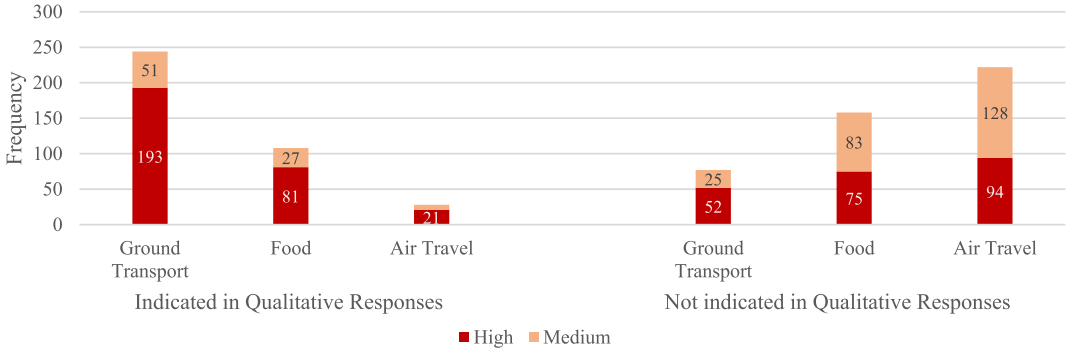

Fig. 2. Comparison of the participants who identified the high impact CL items in the qualitative responses and ranked those actions as high, moderate or low impact on the CL Likert responses (left) with those that did not identify the high impact CL items in the qualitative and ranked those actions as high, moderate or low impact on the CL Likert responses (right).

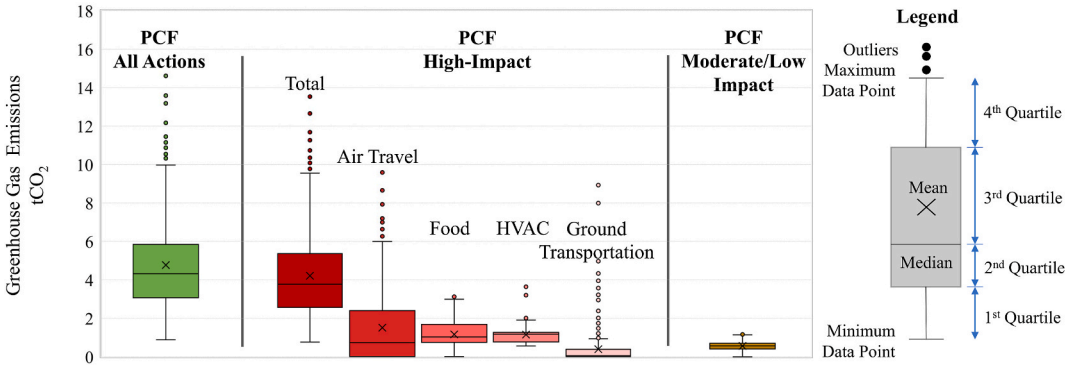

Fig. 3. Overall PCF of participants, separated by high impact actions, subdivided for each high impact action category, and combined moderate and low impact actions.

graphs are available in SI (S5).

The overall PCF was calculated for each participant and separated by specific high impact actions and moderate/low impact actions (Fig. 3). The activities associated with high impact actions together account for more than 87% of the emissions covered by our survey, with air travel having the highest average contribution, followed by diet, HVAC, with ground transportation having the lowest emissions. Looking at the emissions of each high impact action in this study, emissions for ground transportation is notably lower while emissions from food is similar compared to studies/reports measuring carbon footprint for university students in developed countries [51,52,55,120]. We are not aware of any data from prior studies on post-secondary students to compare for HVAC and air travel.

The average PCF calculated for each participant in this study is 4.8 tCO_2. Comparing to similar values for Toronto residents, emissions from HVAC are more than double that of the engineering students and more than 4 times for ground transportation [121]. The engineering students' emissions are also less than half that of the average Ontarian and about a quarter that of the average Canadian [122,123], although we note potential inconsistencies in scope between our emission accounting (limited to a specific subset of activities) and the top-down national/regional emission inventories.

4.3.2. Qualitative PEA, PCF

The participants were also asked an open-ended question to provide the three most impactful actions they personally undertake, if any, to reduce their carbon footprint. Similar to CL, this open-ended question was asked before asking participants about their pro-environmental actions. For the high impact actions, ground transportation was the response by most participants at 260. Fewer participants responded reducing meat, HVAC, air travel or reproduction choices at 71, 33, <10 respectively. The actions in the moderate and low impact categories ranged from 125 to 11 responses. Full tables are presented in SI (S5).

4.3.3. Quantitative and qualitative PEA/PCF comparison

The average PCF for high impact actions of ground transportation, air travel and food and the average thermostat temperatures were compared based on whether or not participants indicated these high impact actions in their open-ended responses. Those who identified the high impact action of food, ground transportation and air travel had a lower carbon footprint for that action compared to

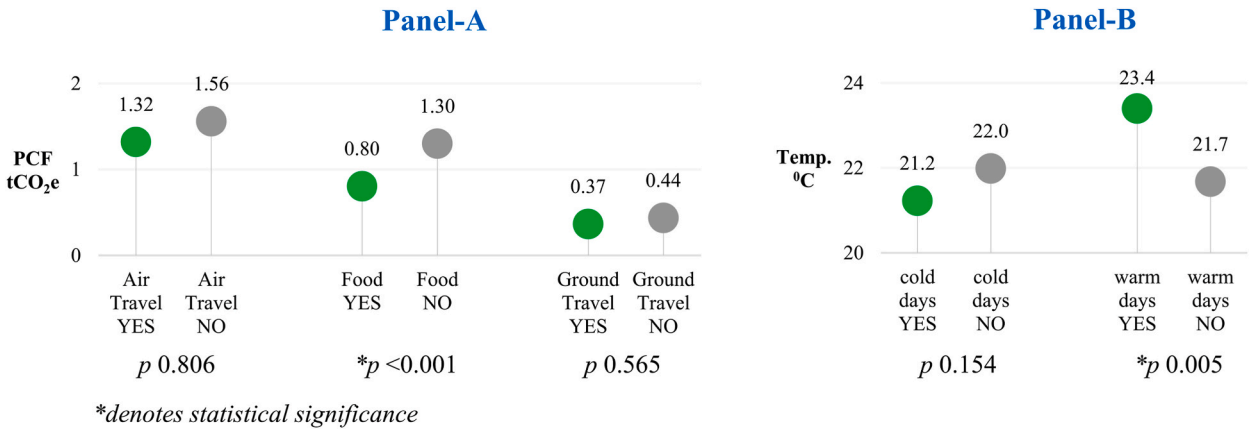

Fig. 4. Comparison of PCF high impact actions with those participants in the open-ended responses who identified the high impact actions (YES) with those who did not (NO). Panel-A compares the responses to their corresponding average PCF while Panel-B compares the responses to the participants average temperatures on cold and warm days.

the participants who did not (i.e., they were more likely to report low meat consumption, less driving, fewer flights in the closed-ended questions) (Fig. 4A). In addition, participants whose open-ended responses were related to HVAC, had a lower average temperature setting on cold days and higher on warm days which would lead to lower associated emissions (Fig. 4B).

4.4. Relationship PEA/PCF, CL

RQ3 How is knowledge about consumption choices related to participants' pro-environmental actions in reducing GHG emissions?

4.4.1. Quantitative association by action type: CL, PCF

PCF scores for each action were tested against the participants ranking the CL high, moderate or low impact actions using ANOVA and Kruskal-Wallis (Fig. 5). Looking at high impact actions and comparing PCF to their corresponding CL, the participants who had the lowest average PCF for air travel, food and ground transportation chose these actions as high impact while participants with the highest PCF chose the actions as low impact. These results suggest that higher CL is associated with lower PCF. Note that not all results were statistically significant with air travel and ground transportation having higher p values.

For the moderate and low impact actions, a similar trend is observed, but only for a subset of actions. In particular, for buying used items, air drying clothes, washing in cold water, buying local, and reducing packaging with purchases, believing the action is high impact (even if incorrect) is associated with acting upon it (lower PCF). For other actions, however, no such trend was found. In particular: using disposable rather than reusable items, reducing food waste, switching to LEDs and turning off the tap when not in use did not show significantly different means among the ranking, so believing these actions are high impact does not lead to a reduction in PCF.

In summary, there is a general (but not universal) trend across many actions showing a positive correlation between regarding the action as high impact, and the propensity to undertake that action. Although we cannot comment on causality with any certainty, the results are suggestive that greater knowledge surrounding which actions are high impact could assist participants in prioritizing their efforts and potentially facilitate more impactful pro-environmental actions. Full tables are available in SI (S5).

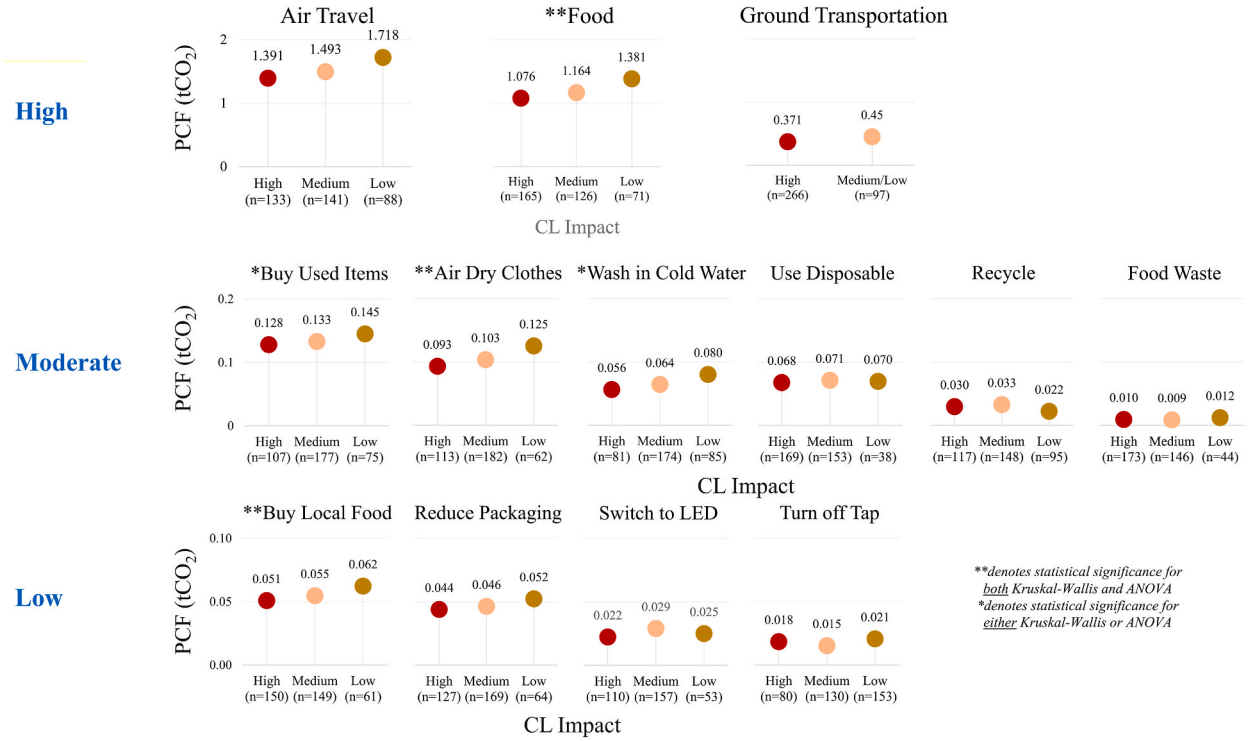

Fig. 5. PCF average yearly score for each action, separated into groups according to whether the participant selected the action as high, medium or low impact in the CL section. Result panels are grouped according to whether the action itself was high, moderate or low. High impact actions in CL correspond to: "avoiding a long-haul flight", "eating a vegan diet" and "switching to public transit" respectively. Note that for ground transportation, medium and low combined as there were fewer that than 10 participants choosing this action as low impact.

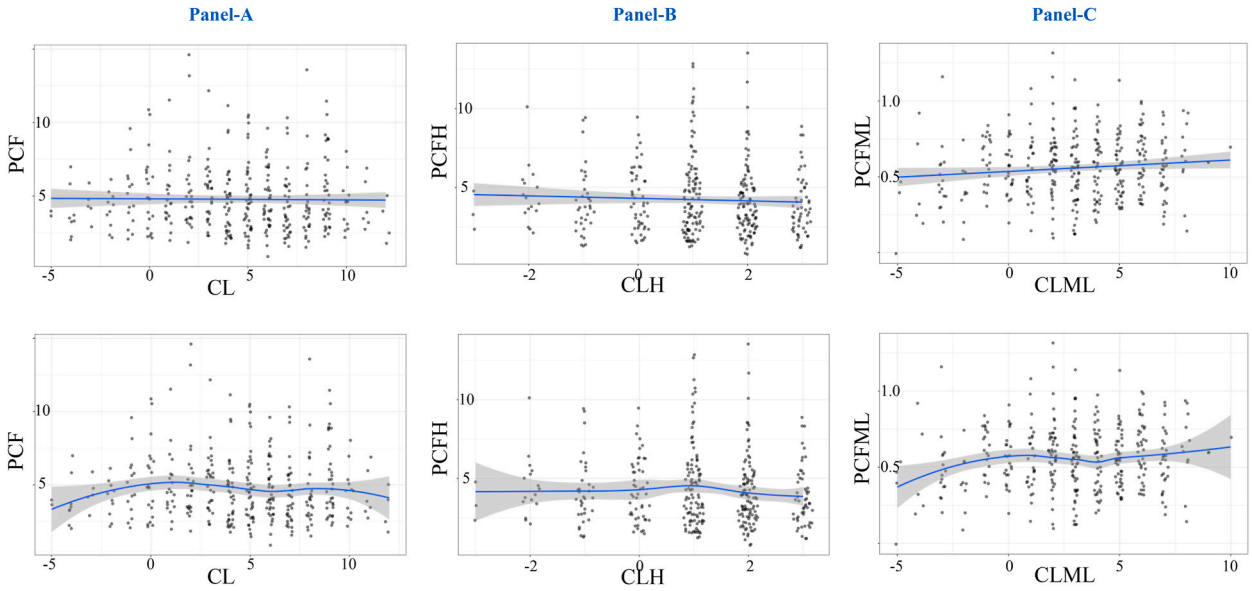

Fig. 6. Regression Results for Personal Carbon Footprint and Carbon Literacy overall (Panel-A), then separated by high-impact actions (Panel-B) and moderate/low impact actions (Panel-C).

4.4.2. *Quantitative association overall: CL, PCF*

The linear (parametric) and Loess (non-parametric) regression between PCF and CL (Equation (1)) shows that overall, there is a very weak relationship, if any, between CL and PCF with a slight negative correlation with CL scores above zero before a plateau around a CL score of 6 (Fig. 6A). Separating the participants' PCF and CL score by high impact (PCFH, CLH) and moderate/low impact actions (PCFML, CLML) show that among high impact actions, there is weak evidence of a mild correlation at high levels of carbon literacy. PCFH carbon footprint and CL scores are fairly flat up to a CLH score of 1, then correlates negatively from a CLH score of 1 onwards (Fig. 6B); in other words, high CLH is very mildly associated with lower PCFH. For moderate/low impact actions, there is evidence that CLML leads to lower action on moderate and low impact items (PCFML), as expected (i.e., knowledge that these actions are less important leads to them being taken less often). PCFML is positively correlated with CLML scores except for a plateau between CLML 0 and 3 (Fig. 6C). These results correlate/agree with ANOVA for high impact and moderate impact actions.

Equation 1: Linear Regression (LR) between Personal Carbon Footprint and Carbon Literacy

$$PEA = \beta_0 + \beta_1 . CL + \varepsilon \quad (1)$$

$$PEAH = \beta_0 + \beta_1 . CLH + \varepsilon$$

$$PEAML = \beta_0 + \beta_1 . CLML + \varepsilon$$

4.4.3. *Qualitative comparison: CL and PEA*

After coding the open-end questions from PEA and CL, the frequencies of participant responses for each theme were compared (Fig. 7), and grouped based on high, moderate and low impact actions. Participants who indicated ground transportation as a high impact action (CL) also performed this action (PEA). However, for the remaining high impact actions, participants identified the action as most important in general (CL) more often than one they personally undertake (PEA). This suggests other important barriers to adopting these actions beyond knowledge or salience. For the moderate and low impact actions, the pattern is somewhat reversed. Participants tend to identify these actions as among the most important they undertake (PEA) even though the actions were not indicated as one of the top three actions one can take in general (CL). For example, almost double the participants engage in reusing items or turning off the lights compared to the number of participants listing these actions as a high impact action. Thus, these participants know/believe that their personal top 3 actions are potentially not among the top 3 in general, again indicating the presence of important drivers beyond knowledge/salience for these items.

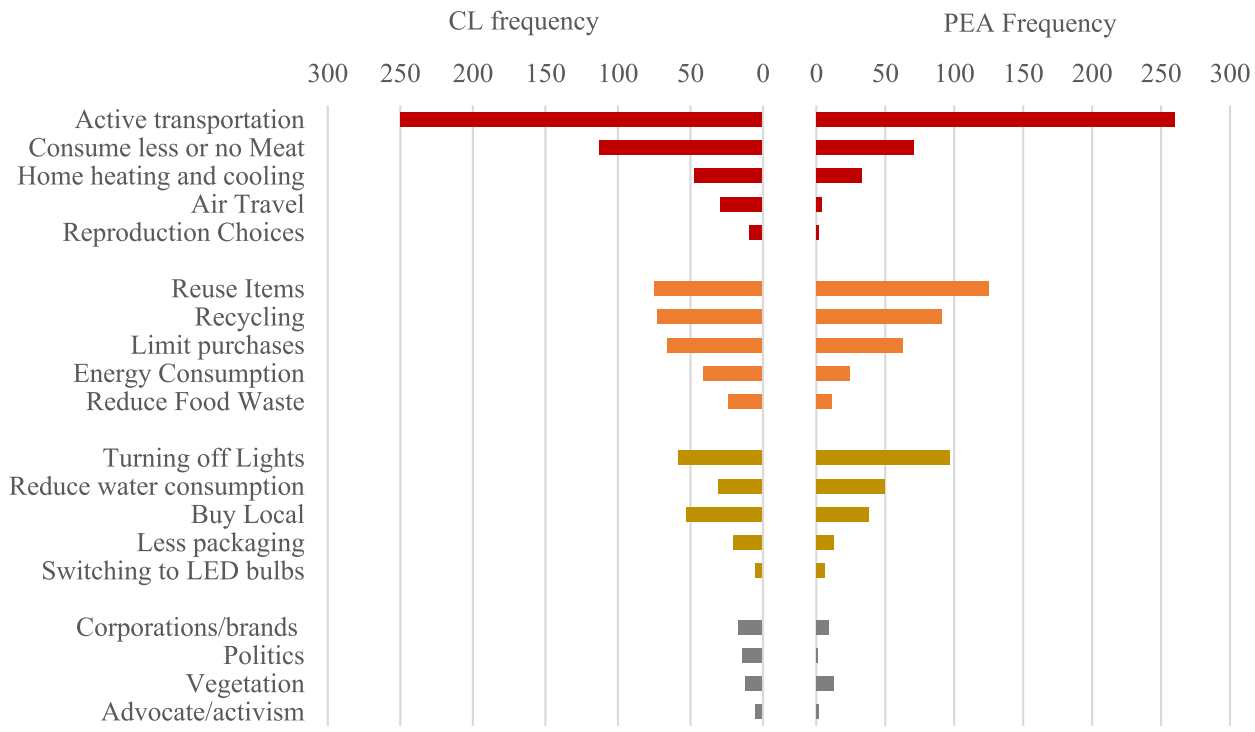

Fig. 7. Comparison of Pro-Environmental Actions and Carbon Literacy themes from the qualitative coding.

5. Study implications

This study found that overall carbon literacy was not generally related to overall personal carbon footprint. However, referring to declarative knowledge, literacy about the environmental impact of some specific actions (effectiveness knowledge) was associated with decreased personal carbon footprints related to those actions (action knowledge). While declarative knowledge may affect one's intent to act, this is not the only motivating factor. Additional factors include social norms, barriers, values, and co-benefits, all of which have been demonstrated under the theory of planned behaviour and environmental psychology [64,67,124,125]. The following sections discuss findings related to particular pro-environmental actions.

5.1. High impact actions

For *ground transportation* results had higher scores for both CL and PEA. Public/active transportation were consistently identified as high impact actions both on the quantitative and qualitative sides for both the CL and PEA constructs. This aligns with data collected by Student Move TO which surveyed the major universities in Toronto in 2015 and 2019 [119]. There may be several reasons for this behaviour. One reason may be that there is ample availability of public transit and the ability to get places within Toronto without a car is relatively easy, that is, there are few barriers to prevent this behaviour. Another reason could be that students may live within close proximity to campus and therefore getting from place to place is convenient without the need to use a car. In addition, it may be financially prohibitive for students to purchase and insure a car. Finally, the traffic congestion in Toronto may increase travel time, hence living without a car might be a time saver.

For *food*, switching to a vegan diet had mixed results for the CL and PEA constructs. Adopting a vegan diet was identified as a high impact action from the CL construct on both the quantitative and qualitative results. However, the PEA does not match the CL in that the quantitative results show that most participants still follow an omnivorous diet. Looking more closely at the breakdown of PEA around diet, it does show that even though participants follow an omnivorous diet, the meat intake is mostly "occasional" (1–6 meals/week). Regarding PEA habits from the qualitative responses, the frequency from the coded theme came back high because reducing and omitting meat from the diet was aggregated. From the qualitative results, participants generally stated the three actions, but a few also expressed reasons for choosing a vegan/vegetarian diet like it being a personal preference rather than environmental choice and the difficulty of switching to a plant-based diet while living in a meat-eating home. We also speculate that reasons for not completely switching to a vegan/vegetarian diet may include lack of options or higher costs.

For *air travel*, there seems to be a potential misconception with respect to its high impact in generating GHG emissions. Quantitatively CL shows a plurality of participants reporting air travel as a moderate impact action, but it should be noted that only a slightly lower number reported air travel as a high impact action and qualitatively only 7% of participants mentioned air travel among the top three items, suggesting low salience for this item. PCF for air travel was lower for participants with higher air travel CL scores.

Reproduction choices were not asked in the PEA quantitative construct due to the demographic being post-secondary students. Having fewer children rarely showed up as a choice in the qualitative answers for both the PEA and CL constructs. The students did correctly report this as a high impact action when asked in the CL construct quantitative section.

5.2. Moderate and low impact actions

The linear regression showed a slight negative correlation between PCF and CL. Certain actions were performed routinely even when participants identified them as medium or low impact actions. For example, participants always or often recycled, turned off the lights or tap when not in use or changed light bulbs to LED even though their CL response showed that they felt it was either a medium or low impact action. The reasons may be that these actions have few or no barriers, are easy to perform or perhaps are based on what they practice from their personal culture, societal norms and trends [67,68]. Conversely, certain actions like air drying clothes, buying local, buying used were seldom or never performed by participants. Reasons could include the inconvenience in performing the actions or personal preference. However, the participants who ranked these actions as high impact did have a lower mean PCF for those actions.

5.3. Limitations and future work

5.3.1. Sample/demographic

The convenience sample survey participants were unevenly distributed by gender, engineering discipline, political leaning and religious affiliation. The sample demographic may be attributed to several factors namely enrollment, the distribution medium, interest in the subject matter, and perceived relevance of the survey based on the researcher's affiliations. Most disciplines had higher numbers of women responding to the survey compared to men, which is generally the opposite of enrollment where more men are enrolled than women. For distribution, a few instructors invited the researcher to present the survey during a lecture, which may have skewed the number of responses as well as the responses by discipline. Civil Engineering had higher numbers of participants and response percentage possibly because the researcher is in that discipline, which may have implicitly encouraged participation. Certain demographics, like the conservative political affiliation and very religious leaning had lower participant numbers in these groups, but we cannot assess for representativeness in the target population. Having more participants overall, randoms samples, higher numbers within certain groups and a streamlined way to distribute the survey may provide a more representative sample and generalizable results.

5.3.2. Instrument, measurement error

No survey can cover every possible contributor to PCF. The instrument itself is undergoing further improvement to remove ineffective questions and to add specificity/depth to the questions around diet, transportation and home energy use and new questions on expenditure to estimate embodied carbon in purchases. These improvements will better capture the participants' PCF, however, will still not be a complete representation.

In the opened-ended questions, participants could choose only 3 most impactful actions in the qualitative responses. This limit may artificially restrict ideas with high salience beyond the top 3. Some other themes came out of qualitative responses, such as political engagement, focusing on corporations, sustainable or ethical purchasing choices and limiting purchases. These options were not included in the multiple-choice section of the survey and may be areas for further inquiry.

Our PEA measurement may also suffer from biases associated with self-reporting. Directly measuring PEA would be more accurate but also more invasive and time consuming. There is also uncertainty in the LCA results (especially over time/space).

5.3.3. Future work

Potential ideas/needs for future work include extending the survey to additional academic units/departments at UofT, engineering students at other universities within Canada and worldwide, and longitudinal surveying of past participants. Additional administration would enable comparison among different groups and allow tracking of results over time.

Work is also currently ongoing to update the instrument to add additional resolution to certain categories (e.g., duration of flights taken, road trips, type of heating system at home) and expand the survey to capture other activities such as expenditure patterns. Further exploration with the data to include analyses around participant characteristics and qualitative typological profiling may provide additional information about the participants to aid in knowledge building and emissions reductions pathways.

6. Study conclusions

This section provides a brief summary of the novelty, key findings, limitations, and future work of the study. For this study, 364 engineering undergraduates at the University of Toronto was surveyed to capture two latent constructs of carbon literacy (CL) and personal carbon footprints (PCFs). Although prior work has assessed CL and PCFs, few prior studies have investigated the relationship between them. A PCF was calculated for each participant using a life-cycle assessment (LCA) approach. Carbon literacy was best for some high impact actions like ground transport and diet, and less so for air travel. There was mixed carbon literacy for the moderate and low impact actions. In general, belief that an action was high impact correlated with lower PCF for that activity. However, the overall relationship between pro-environmental action and carbon literacy was weak.

Subsequent to completing this study, future work is planned. There were limitations associated with selecting certain activities

measured for estimating the participants' personal carbon footprint and running a convenience sample. The survey instrument has been enhanced to collect additional data that will refine the carbon footprint calculations from this study. The enhancements include deeper insights into transportation (ground and air), climate control and personal spending. The enhanced survey will be extended to include all units across three campuses at the University of Toronto. This study and planned extensions provide insight into the role of personal action in reducing greenhouse gas emissions and will require periodic follow-up across a range of population to monitor progress in public carbon literacy and associated personal carbon footprints.

Ethics declarations

This study was reviewed and approved by the Research Ethics Board of the University of Toronto, with the approval number: Protocol Number: 40378.

All participants/patients (or their proxies/legal guardians) provided informed consent to participate in the study.

All participants/patients (or their proxies/legal guardians) provided informed consent for the publication of their anonymized case details and images.

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Data availability

Has data associated with your study been deposited into a publicly available repository? NO.

The authors do not have permission to share data.

CRediT authorship contribution statement

Sherry-Ann Ram: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Heather L. MacLean:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Deborah Tihanyi:** Writing – review & editing, Supervision, Validation. **Liam Hannah:** Writing – review & editing, Validation. **I. Daniel Posen:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Sherry-Ann Ram reports financial support was provided by Mitacs Research Training Award. Sherry-Ann Ram, I. Daniel Posen, Heather MacLean, Deborah Tihanyi reports a relationship with University of Toronto Faculty of Applied Science & Engineering that includes: employment and funding grants. As a follow-up to the response provided in Question 2, authors I. Daniel Posen, Heather MacLean, Deborah Tihanyi are professors and Sherry-Ann Ram is a PhD student at the University of Toronto within the Faculty of Applied Science and Engineering. This is the Faculty in which the survey for the study was administered.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e20634.

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