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Agricultural Life Cycle Assessment of Saffron (*Crocus sativus* L.) Cultivation in Türkiye

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Abstract
Saffron (*Crocus sativus* L.) is regarded as an important crop in Turkish agriculture that needs to be investigated to produce sustainable agricultural products. In this study, the environmental emissions of saffron cultivation and their environmental effects were determined for saffron production. The environmental effects of saffron production were assessed using agricultural life cycle assessment. Environmental effect categories were obtained using the CML-IA Baseline method. Original SimaPro 8 software was used to calculate the environmental effects. The results showed that the average stigma yield of saffron was 4.81 kg ha^{-1}. According to the agricultural life cycle impact assessment of saffron production, environmental effects caused marine aquatic toxicity by 75.77%, while local effects accounted for 86.79% in its agricultural life cycle interpretation. Also, the global warming (climate change) value was calculated as 63.52 kg $CO_{2\text{-eq}}$ kg $saffron^{-1}$ (305.53 kg $CO_{2\text{-eq}}$ ha^{-1}).

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1. Introduction

Türkiye is one of the world's richest countries in terms of endemic plants. The number of endemic plants in Türkiye is around 3750. The ratio of these endemic plants to all plants in the flora is approximately 33%. On the other hand, the number of endemic plants facing extinction in Türkiye constitutes 23% of the total number of plant species in the flora (Asil, 2015; Şaltu, 2002). One of these threatened endemic plants is saffron (*Crocus sativus* L.), one of the most expensive endemic plants in the world, also known as red gold (Figure 1).



Figure 1. Saffron (*Crocus sativus* L.) flower (Ayva, 2019)

Saffron accentuates myth, magic, medicine, and meals all over the world, with legendary "roots" that can be traced back through history and into story. From the cradle of civilization to Cleopatra's courts, from the Sumerian and Persian kingdoms to Greek and Biblical divinity, and from the Near and Far East to the European and American West, saffron appears everywhere, both in trade and in tale (Golmohammadi, 2014). Saffron is an autumn-flowering, high-value, low-volume spice crop that grows throughout Mediterranean Europe and Western Asia between 10° west and 80° east longitudes and 30° to 50° north latitudes. At present, saffron production is limited to Iran and countries of older civilizations such as India, Spain, Italy, Greece, and Türkiye (Yasmin and Nehvi, 2013). According to the latest statistics for saffron trade in 2019, Iran is the world's largest producer of saffron, supplying 430 tons of the total 450 tons of saffron produced worldwide (≈96% of global saffron production). India, producing only 22 tons of saffron annually, ranks second. Other saffron-producing countries, based on their share of global saffron production, include Greece (7.2 tons), Afghanistan (6 tons), Morocco (2.6 tons), Spain (2.3 tons), Italy (1 ton), China (1 ton), and Azerbaijan (0.23 ton) (Anonymous, 2026a). As the world's leading exporter of saffron, Iran's share in the global saffron market is 42%, worth $202.50 million in 2025 (Anonymous, 2026b). Some regions of Türkiye (the Deyrulzafaran Monastery in Mardin and Safranbolu in Karabük) are considered to be the origin of saffron. Although Türkiye is a region of origin of saffron, its production is very low. In recent years, saffron production has been expanded with the support of the Republic of Türkiye Ministry of Agriculture and Forestry. Saffron is produced in a non-mechanized agricultural system. Its production and processing are generally performed manually, and its very high price is relatively linked to the intensive hand labor required for daily flower picking, separation of the stigmas, and drying (Khanali et al., 2016; Khanali et al., 2017). More efficient energy use and better environmental management in saffron cultivation are important issues for providing a sustainable production system. Therefore, assessing the environmental impacts of saffron production was recognized as an important tool for farmers, producers, and decision-makers in agriculture (Khanali et al., 2017). Environmental impacts (acidification, ecotoxicity, eutrophication, greenhouse gas

emissions, photochemical oxidation, etc.) play a key role in appraising or comparing the effectiveness of various production systems and determining the environmental sustainability of farming (Mehmeti et al., 2024). The agricultural life cycle assessment (Agricultural LCA) method is used to determine environmental impacts. Agricultural LCA is a method used to determine the environmental effects of inputs in the agricultural production system, from soil cultivation to crop harvest, according to environmental impact categories. The Agricultural LCA cycle is classified as cradle-to-gate (Hayashi et al., 2005), while the LCA cycle is classified as cradle-to-grave. Recently, LCA studies of agricultural products such as apple (Bamber et al., 2020), chickpea (Ghaderpour et al., 2020), bell pepper (Naderi et al., 2019), cuccumber (Zarei et al., 2019), cotton (Shah et al., 2018), peach (Nikkhah et al., 2017), strawberry (Romero-Gámez and Suárez-Rey, 2020; Tabatabaie et al., 2016), sweet sorghum (Tutar et al., 2024; Eren and Öztürk, 2021) and tomato (Zarei et al., 2019) have increased in the literature. Although many studies on the agricultural LCA of saffron production have been reported in the literature (Mehmeti et al., 2024; Khorramdel et al., 2020; Khanali et al., 2017), there has been no study on the agricultural LCA of saffron production in Türkiye. Therefore, in this study, the agricultural LCA method was used to determine the environmental impacts of saffron production in Türkiye.

2. Material and Method

2.1. Selection of case study area and data collection

The research was carried out in the field at was carried out on the land of a farmer who grows saffron in the Kırıkhan district (36°30' N - 36°20' E) of Hatay province. The experimental area is shown in the Figure 2. The elevation of the research area is 155 meters above sea level.



Figure 2. Experimental area (Ayva, 2019)

In the experimental area, which has a humid climate, the total precipitation amount in the vegetation periods (between Oktober and May) was 1064.6 mm and the average temperature was 12.6 °C. During the cultivation of the saffron, there is temperature demand of 10-15 °C and a water requirement of 300 mm. The temperature during the trial period met the temperature requirements of the plant during its growing season. Furthermore, as saffron is a winter plant, the rainfall during the growing season met its water requirements, thus eliminating the need for irrigation. According to the results of soil analysis carried out in the experimental area, the soil was salt-free, clayey, low in organic matter (Ayva, 2019).

2.2. Cultural practices of saffron production

Cultural practices and maintenance processes in the production of saffron were carried out as follows (Ayva, 2019). - Tillage: The soil was plowed to a depth of 20-25 cm using a plough with 3 shocks (job width 1.10 m and mass 1220 kg). A Ford 6610 tractor (mass 2583 kg) was used for this operation.

- Planting: In the first half of October, planting was done at a depth of 10 cm with 30 cm row spacing and 10 cm row length (Figure 3). The planting was done so 1667 kg of corms fell per hectare**.**
- Maintenance: Weed removal was performed manually a total of four times (in mid-November, mid-December, mid-March, and mid-April) during the period from planting the saffron plant to harvesting the saffron corms. Five male workers were employed for the first weeding task. The other weeding tasks were performed by 7, 9, and 9 male workers, respectively.



Figure 3. General appearance of the corm bed after planting (Ayva, 2019)

- Harvest: Saffron flower (Figure 4) harvesting began in early November and ended in mid-December. It was harvested a total of 15 times by hand with one male worker. It was then sorted by two female workers (Figure 5). Saffron corm harvesting was carried out at the end of July over two days with 13 male workers.



Figure 4. The general appearance of the first harvested saffron plant (Ayva, 2019)



Figure 5. Saffron plant stigmas separated from their flowers (Ayva, 2019)

2.3. Determination of environmental impacts

Agricultural LCA was carried out in four stages. These are (Tutar et al., 2024):

i. Goal and scope definition

This study was conducted to identify the environmental impacts arising during saffron stigma production. As saffron is a difficult-to-produce and labor-intensive product, the primary factor determining its price is the quantity of saffron stigma. For this reason, 1 kg of saffron stigma was adopted as the functional unit for saffron production. To this end, the system boundary was defined as shown in Figure 6.

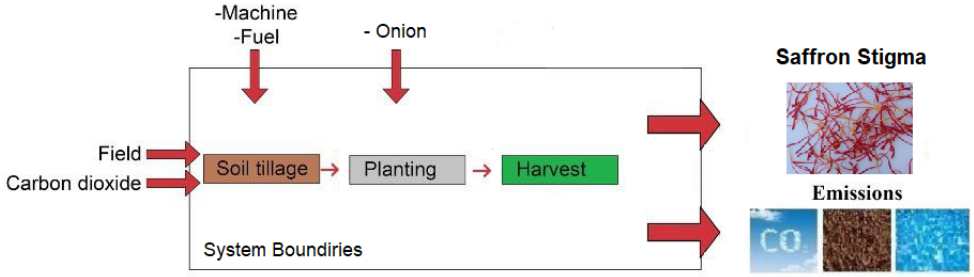

Figure 6. System boundaries of the production system

ii. Life cycle inventory (LCI)

The following assumptions were made in order to carry out the life cycle inventory analysis of the production system (Table 1). Then, inventories of the production system were made. The mass balance inventory (agricultural inputs and outputs used during production) values in the production system are given in Table 2.

Table 1. Assumptions

Assumptions	Answers
Slope of fields	No slope
Cultivability of fields	Cultivable
Type of agriculture	Rainfed agriculture
Drainage	None
Clay content of soil (%)	77.00
Humus content of the soil (%)	1.96
Plant potential root depth (cm)	-
Soil erosion (K) factor	Ignored
Fertilization	None
Machine to prevent ammonia losses	Not used

Table 2. Mass balance inventory

Inventories	Unit	Amount per ha
Land use	ha	1.00
Disel fuel	L	92.60
Saffron corms	kg	1666.67
Saffron stigma yield	kg	4.81

iii. Life cycle impact assessment (LCIA)

According to the results obtained from the life cycle inventory analysis, the CML-IA Baseline methodology was used in accordance with ISO 14040 standards for the evaluation of the environmental impacts of the saffron production system. Potential environmental impacts (characterization values) were calculated with SimaPro 8.0.5.13 Analyst software based on the CML-IA Baseline methodology. This CML-IA Baseline methodology includes 11 environmental impact categories (Table 3). After calculating the characterization values, normalization

values were calculated by performing normalization with the software. Normalization was done in order to evaluate the impact categories among themselves (Tutar et al., 2024).

Table 3. Impact categories and characterization units according to the CML-IA Baseline model (Tutar et al., 2024)

Impact Categories	Characterization Unit
Abiotic depletion	kg Sb_{-eq}
Abiotic depletion (fossil fuels)	MJ
Global warming (GWP100a)	kg CO_{2-eq}
Ozone layer depletion (ODP)	kg $CFC11_{-eq}$
Human toxicity	kg $1.4\text{-}DB_{-eq}$
Fresh water aquatic ecotoxicity	kg $1.4\text{-}DB_{-eq}$
Marine aquatic ecotoxicity	kg $1.4\text{-}DB_{-eq}$
Terrestrial ecotoxicity	kg $1.4\text{-}DB_{-eq}$
Photochemical oxidation	kg C_2H_{4-eq}
Acidification	kg SO_{2-eq}
Eutrophication	kg PO_{4-eq}

iv. Interpretation

Finally, based on normalization values, the global, regional and local impacts of the saffron stigma production system were evaluated and interpreted.

3. Results and Discussion

3.1. Evaluation of characterization and normalization results

The comparison of the impact categories based on the normalization results is shown in Figure 7.

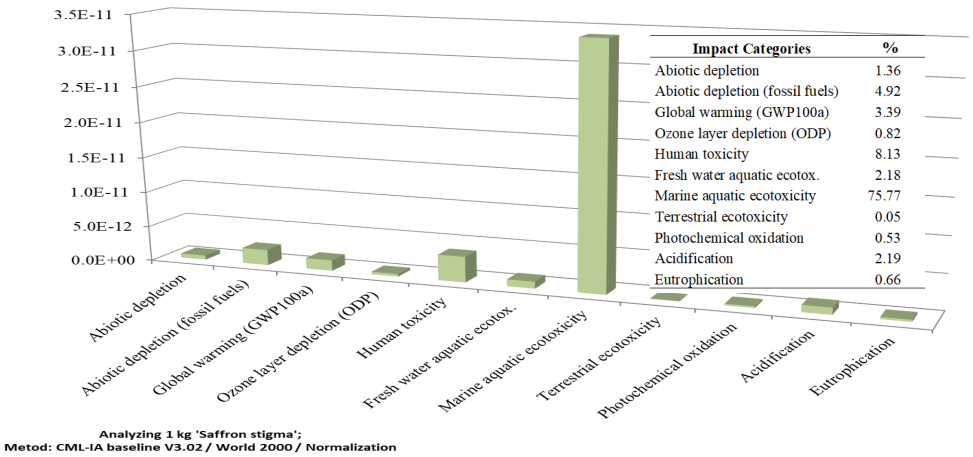

Figure 7. Comparison of normalization values on the basis of impact categories

According to Figure 7, the production of saffron caused the most marine aquatic ecotoxicity (75.77%). Marine aquatic ecotoxicity is followed by the effects of human toxcitiy (8.13%), abiotic depletion (fossil fuels) (4.92%) and global warming (GWP100a) (3.39%), respectively. The effects of abiotic depletion, ozone layer depletion, fresh water aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication comprised less than 2.50% in the production system, and can be ignored. As a result of the impact assessment of saffron production, Table 4 given the characterization values and related hotstops for each impact category. Hotspots represent the inputs and direct emissions that contribute most significantly to the impact category.

Table 4. Characterization values obtained from the LCIA of 1 $kg_{saffron}$ production

Impact categories	Characterization unit	Values	Hotspots
Abiotic depletion	kg Sb_{-eq}	0.0001276	Diesel fuel
Abiotic depletion (fossil fuels)	MJ	839.04	Diesel fuel
Global warming (GWP100a)	kg CO_{2-eq}	63.50	Tillage
Ozone layer depletion (ODP)	kg $CFC11_{-eq}$	0.000083	Diesel fuel
Human toxicity	kg 1.4-DB_{-eq}	9.39	Plough (indirect)
Fresh water aquatic ecotoxicity	kg 1.4-DB_{-eq}	2.31	Plough (indirect)
Marine aquatic ecotoxicity	kg 1.4-DB_{-eq}	6582.59	Diesel fuel
Terrestrial ecotoxicity	kg 1.4-DB_{-eq}	0.0269	Plough (indirect)
Photochemical oxidation	kg C_2H_{4-eq}	0.00878	Diesel fuel
Acidification	kg SO_{2-eq}	0.234	Tillage
Eutrophication	kg PO_{4-eq}	0.0469	Tillage

When we assess the four impact categories shown in Figure 7 that negatively affect saffron production from an environmental perspective according to Table 4;

- Marine aquatic ecotoxicity value was calculated as 6582.59 kg 1.4-DB-eq $kg_{saffron}^{-1}$ and the agricultural application causing the most marine ecotoxicity was diesel fuel consumption. Khanali et al. (2017) calculated the marine aquatic ecotoxicity on saffron stigma production in Iran as 8370.56 1.4-DB-eq $kg_{saffron}^{-1}$. The value calculated in this study was found to be lower than the value calculated by Khanali et al. (2017). The absence of pesticide use in this study positively influenced the lower value.
- Human toxicity value was calculated as 9.39 kg 1.4-DB-eq $kg_{saffron}^{-1}$ and the agricultural application causing the human toxicity was indirect plough production. Khanali et al. (2017) calculated the human toxicity on saffron stigma production in Iran as 41.38 1.4-DB-eq $kg_{saffron}^{-1}$. The value calculated in this study was found to be lower than the value calculated by Khanali et al. (2017).
- Abiotic depletion (fossil fuels) value was calculated as 839.04 MJ $kg_{saffron}^{-1}$ and the agricultural application causing the abiotic depletion (fossil fuels) was diesel fuel consumption. Khanali et al. (2017) calculated the only abiotic depletion on saffron stigma production in Iran as 1.28 kg Sb_{-eq} $kg_{saffron}^{-1}$. The value calculated in this study was found to quit low (0.0001276 kg Sb_{-eq} $kg_{saffron}^{-1}$) than the value calculated by Khanali et al. (2017). In this study, the absence of chemical fertilizers had a positive effect on the low value.
- Global warming (GWP100a) value was calculated as 63.50 kg CO_{2-eq} $kg_{saffron}^{-1}$ and the agricultural application causing the Global warming (GWP100a) was tillage process. In studies carried out on the saffron, this value was obtained as 296.16 kg CO_{2-eq} $kg_{saffron}^{-1}$ (Khanali et al., 2017)) and 2164 kg CO_{2-eq} $kg_{saffron}^{-1}$ (Mehmeti et al., 2024). The value calculated in this study was found to be lower than the calculated values of both studies. In this study, the absence of chemical fertilizers had a positive effect on the low value.

3.2. Interpretation

When all the effects are evaluated together (Figure 8), the production of 1$kg_{saffron}$ caused the largest impact on a local (86.79%). The global impact was followed by the global (10.49%) and the regional impacts (2.72%).

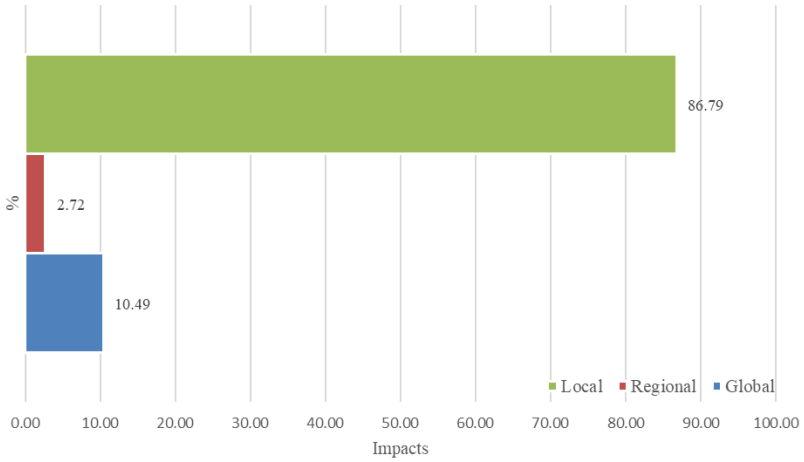

Figure 8. Comparison of impact categories with each other

3.3. Local impacts

When the impact categories causing local effects were evaluated among themselves, it was determined that the impact of marine aquatic ecotoxicity was quite high (87.30%). This impact also has a very negative effect on the local environment. Therefore, there may be a decrease in marine life (if the location is close to the sea) and biodiversity in the area where 1 $kg_{saffron}$ is cultivated (Figure 9).

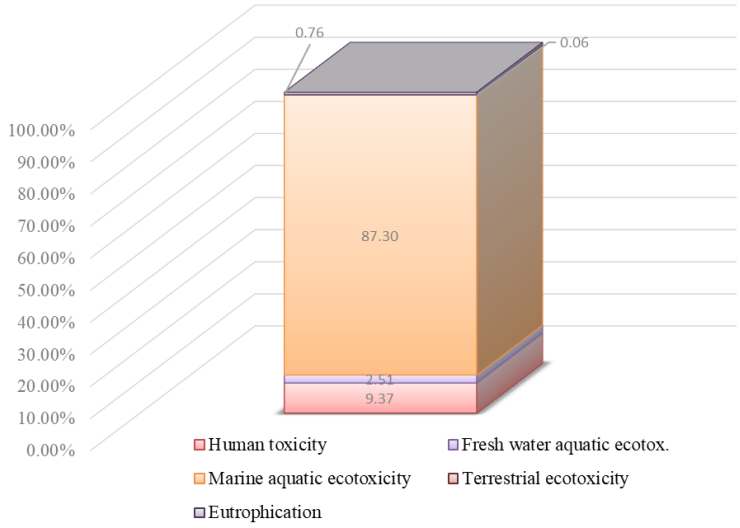

Figure 9. Stacked table of local impacts

The marine aquatic ecotoxicity is followed by human toxicity. Human toxicity is followed by the fresh water aquatic ecotoxicity. Therefore, it is assumed that fresh water organisms and commercial or recreational fishing may decline in areas where saffron is cultivated.

3.4. Global impacts

When the impact categories causing global impacts are evaluated among themselves, it has been determined that abiotic depletion (fossil fuels) has the greatest impact on global effects (46.95%). Therefore, it is assumed that natural resources to be passed on to future generations, especially fossil fuels, may decrease. Transportation and industry that rely on fossil fuels will be significantly negatively affected, and economic difficulties may be observed (Figure 10)

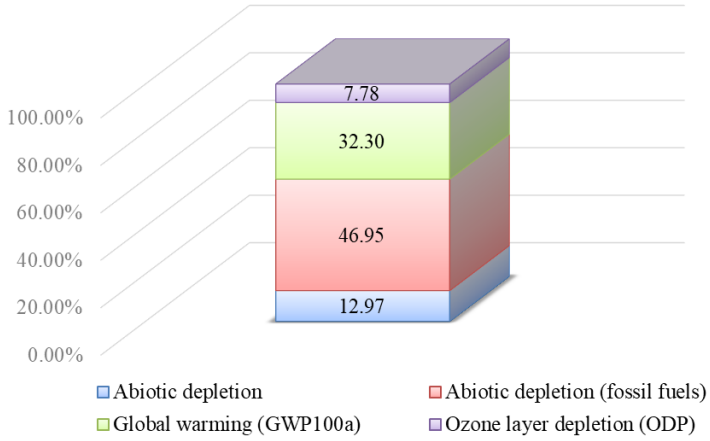

Figure 10. Stacked table of global impacts

Another factor contributing significantly to the global impact is global warming (GWP100a) (32.30%). Consequently, melting at the poles, loss of moisture in the soil, seasonal variations, changes in wind and ocean currents, and, in short, climate change are anticipated. As a result, health problems may arise in living organisms within the ecosystem, particularly in humans.

3.5. Regional Impacts

When the impact categories causing regional impacts were evaluated among themselves, it was determined that acidification (80.40%) caused the most regional impact. Therefore, it is assumed that acid rain, corrosion, and acidification in wet areas may occur in the region where the product is grown. This may also damage other products grown in the area. Materials may deteriorate (Figure 11).

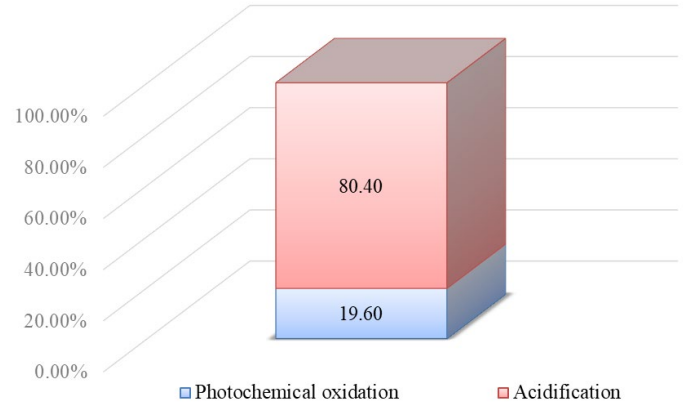

Figure 11. Stacked table of regional impacts

4. Conclusion

According to the percentage distribution of normalized values in the agricultural LCA of saffron cultivation for stigma production, the highest environmental impact was marine aquatic ecotoxicity, with a rate of 75.77%. According to the agricultural LCA, production has a local impact of 86.79%. Marine aquatic ecotoxicity (87.30%) is also more significant within local impacts. When evaluated in terms of its impact on climate change, the GWP 100a value was calculated as 63.50 $kgCO_{2\text{-}eq}$ kg $stigma^{-1}$ (305.53 $kgCO_{2\text{-}eq}$ ha^{-1}). According to studies on saffron, this value is quite low, but compared to other agricultural products, it is relatively high. The use of diesel fuel, particularly during the tillage process in agricultural production, has been identified as the environmental pollutant with the highest impact. Fuel consumption should be

monitored, and optimization efforts should be undertaken. Additionally, priority should be given to environmentally friendly agricultural machinery that incorporates energy-efficient and precision farming practices. Agricultural LCA should be conducted for many products, and the environmental impacts of their cultivation processes should be determined. Evaluation studies on the agricultural LCA of agricultural products intended for export should be increased in Türkiye, and databases should be created.

Declaration of Author Contributions

The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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Ethical Committee Approval

This study did not involve human or animal subjects; therefore, ethical approval was not required.

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