



Technical Innovations & Patient Support in Radiation Oncology

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Green radiotherapy: AITRO survey on sustainability awareness among Italian radiation therapists

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ABSTRACT

Introduction: Sustainability has become a growing priority in healthcare, including radiotherapy. Promoting sustainable practices is crucial to reducing environmental impact, optimizing resource use, and improving departmental efficiency. This study, conducted by the Italian Association of Radiation Therapy and Medical Physics Technologists (AITRO), aimed to explore the culture of sustainability among Italian radiation therapists (RTTs).

Methods: A nationwide anonymous survey was developed by a focus group of RTTs from AITRO's to ensure clinical relevance. The 17-question questionnaire, divided into five thematic areas, was distributed during the AITRO National Congress 2024 and via social media for two additional weeks. Data were analyzed using descriptive statistics and non-parametric tests.

Results: A total of 191 valid responses were collected with median age of 38 years and balanced geographical representation across Italy. Only 14.7 % had attended sustainability-focused training, and 17.8 % had participated in related events. The overall knowledge level on sustainability was moderate (median = 3/5), with 38.2 % reporting limited knowledge. A significant association was found between attending sustainability sessions and higher knowledge scores ($p < 0.05$). Sustainable initiatives were reported by 41.9 % of respondents, with slightly higher adoption in Northern centers. Barriers to implementation included insufficient training and lack of structured guidance.

Conclusions: Italian RTTs demonstrate moderate awareness of sustainability, with limited training and heterogeneous adoption of sustainable practices. These findings highlight the need for structured educational programs, enhanced interprofessional awareness, and institutional support. Scientific Association such as AITRO can play a pivotal role in promoting and fostering sustainability policies in radiotherapy.

Introduction

Climate poses a significant threat to public health, placing a responsibility on the healthcare sector to actively address its impact [1]. The healthcare sector is one of the main sources of environmental pollution [2], and in Europe it is responsible for about 12 % of the

sector's global climate footprint. As the largest operational units within the system, hospitals have a crucial role in driving sustainable development, consuming 50–80 % of healthcare resources and contributing 35 % of sector emission [1]. Their significant contribution to greenhouse gas (GHG) emissions, resulting from energy consumption, transportation, and the production, use, and disposal of medical resources,

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highlights the urgent need for targeted sustainability efforts within hospital operations [3,4]. Sustainability is one of the relevant challenges of the 21st century to be addressed in the healthcare context [5]: climate change contributes to multiple health threats, including reduced air quality and pollution, ultraviolet radiation, disruptions in food and water supply, environmental toxicants, and infectious agents, which may increase the incidence and burden of chronic diseases such as cancer [6,7]. The topic of sustainability in the healthcare sector represents a multidimensional perspective, as various fields can be involved, starting from social, economic and environmental dimensions [8]. Hospitals play a crucial role in promoting sustainable practices, including resource management, sustainable food and transport and waste minimization [9]. A systematic review of environmental sustainability shows that while research on hospital buildings, engineering and the technologies used in them is relatively advanced, less is known about the clinical, psychological and social factors that influence how healthcare professionals interact with these buildings and technologies [10]. Although the carbon footprint of cancer treatment has not yet been measured, it is likely to make a significant contribution given the focus on chemotherapy, radiation treatment and the frequency of hospitalization [11]. Recent studies have begun to quantify the environmental impact of external beam radiotherapy (EBRT), providing methodological frameworks and multi-center data that highlight major drivers of emissions such as patient transportation, equipment acquisition and maintenance, and direct energy use [12,13]. In particular, patient travel has been identified as a significant contributor, and reducing the number of treatment fractions has been shown to lower CO₂ emissions while simultaneously improving patient outcomes [14]. The environmental impact has been examined in previous studies and accounts for a significant share of CO₂ emissions. They are primarily caused by patient travel, which is directly linked to the fractionation scheme [7,15–17]. Despite the focus of several studies on the carbon footprint of treatment delivery, other phases of treatment—such as the impact of CT simulation or other imaging methods used for treatment planning—have not been exhaustively considered, as reported in a recent review [18]. Several other environmental impacts, such as the effect on soil, air, and water quality, assessed through a life cycle assessment (LCA), must be taken into account in connection with radiotherapy [19]. These include the emissions generated by disposable and reusable consumables, the direct electricity consumption of the equipment, the energy consumption for others and various purposes in the department and the travelling of staff and patients [20]. In an effort to provide safe, effective and equitable patient-centered care, various emission reduction measures have been recognized and proposed, such as the use of telemedicine, hypofractionation and the use of clean energy at the institutional level [18,20]. These initiatives are consistent with the recently proposed Green Radiotherapy Framework (GRF), which provides a structured approach to support radiotherapy departments in systematically reducing their environmental impact while maintaining treatment quality [21]. Also, the competitive role of modern radiotherapy is being evaluated in comparison to other therapeutic options, demonstrating SBRT may enhance workflow sustainability, reducing costs by 40 % and energy consumption to 1 % of a two-hour surgery usage [22]. As widely reported in the literature, the active participation and commitment of healthcare professionals is crucial for the effective implementation of sustainable development in the various areas of healthcare [1,23–25]. Knowledge and awareness of sustainability issues are crucial for healthcare professionals to actively contribute to improving sustainable development. Healthcare professionals' lack of commitment to environmental issues can be a barrier to progress on sustainability in hospitals [26]. Italian Association of Radiation therapist and Medical physics technologist (AITRO), has launched a national survey to explore the perceptions, knowledge, and practices of Radiation Therapist (RTT) regarding sustainability. The study aims to identify barriers, challenges, and opportunities to develop concrete initiatives and foster a culture of sustainability in Italian radiotherapy centers. (See Fig. 1)

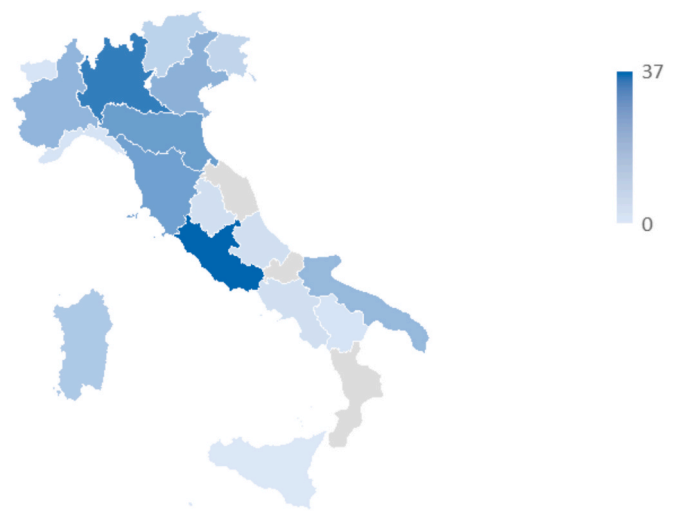


Fig. 1. Geographic distribution of survey participants (absolute numbers).

Methods

• Survey Design

The study used an anonymous questionnaire to assess the culture of sustainability among RTTs in Italy. The questionnaire was developed by a dedicated focus group made up of 8 RTTs from the Italian Association of Radiotherapy Technologists (AITRO) Scientific Committee to ensure that the content was relevant, accurate and in line with the realities of clinical practice. Before distribution, the questionnaire underwent a qualitative review by members of the AITRO Scientific Committee not directly involved in the design, together with the Executive Board, who provided feedback on the clarity and relevance of the items. An electronic questionnaire was implemented on the Microsoft Forms platform to facilitate access and data collection. All responses were collected in aggregated form to ensure anonymity and avoid individual identification. The questionnaire was carefully designed to capture a comprehensive understanding of RTTs' knowledge, attitudes and practices in relation to sustainability in radiotherapy. It consisted of 17 questions divided into five thematic sections:

- o Demographic data: Collected important background information such as age, work experience, work environment and geographic distribution to contextualize the answers.
- o Knowledge and perception of sustainability: Assessed RTTs' awareness of environmental sustainability, their understanding of its relevance in healthcare and their perception of its impact on radiotherapy.
- o Sustainable initiatives and measures in radiotherapy: The existing environmentally friendly practices in radiotherapy departments were examined, including energy saving measures, waste reduction and resource optimization.
- o Barriers and challenges: Investigated barriers to adopting sustainable practices, such as lack of institutional support, financial constraints or limited awareness.
- o The role of AITRO: Analyzed how AITRO can support and promote sustainability through training, advocacy and policy recommendations.

In order to gain both quantitative and qualitative insights, the questionnaire contained a mixture of multiple-choice questions and statements on a five-point Likert scale. This combination allowed trends to be analyzed in a structured way while providing space for participants to express personal opinions and experiences.

The target audience for this study was exclusively RTTs currently

working in Italy to ensure that the results reflected the perspectives of professionals actively working in the field of radiotherapy. The questionnaire design and reporting are in line with the recommendations of the ESTRO guidelines for survey-based research [27]. All questionnaires are reported in Supplementary material.

• Survey distribution

The survey was distributed during the AITRO National Congress 2024, which took place in Florence on 25–26 October 2024, via a QR code displayed during the event, and the weblink was available for a further two weeks via the association's official social media channels. This approach maximized participation and ensured a diverse representation of RTTs from different geographical areas. Informed consent was obtained from all subjects prior to their voluntary participation in the study. The survey introduction emphasized the general privacy policy, the study's purpose, and the collection of only aggregated and anonymous data. The estimated time required was approximately 5 min.

• Statistical analysis

Descriptive statistics were used to summarize the collected data. To assess the normality of the data, the Shapiro–Wilk test was performed, revealing a deviation from normality for all numerical variables (p -value < 0.05). Consequently, continuous variables were reported as the median (first quartile Q1 – third quartile Q3), while ordinal and nominal data were presented as percentages and ratio values. For Likert scales, quartiles were reported to provide the interquartile range (IQR), as the minimum and maximum values are almost always 1 and 5, and the IQR better captures variability around the median.

Given this, non-parametric tests were used for inferential analysis. To compare differences between two independent groups, we used the Wilcoxon rank-sum test (Mann–Whitney U test).

To assess the relationships between numerical variables, the Spearman correlation coefficient was computed. A significance level of $p < 0.05$ was considered for all statistical analyses. All analyses were conducted using RStudio (Version 2021.09.1, R Foundation for Statistical Computing).

Results

A total of 195 responses were collected. After data validation, 191 responses were considered valid for analysis. Four responses were excluded: two from respondents outside Italy and two from individuals who do not work in radiotherapy.

Participation in sustainability-related training and events remains relatively low. Only 14.7 % of respondents reported attending formal training courses on sustainability, while 85.3 % had never taken part in such educational programs. Similarly, participation in events or congresses featuring sustainability-related sessions was limited, with only 17.8 % of respondents reporting attendance, compared to 82.2 % who had never participated. A regional disparity was observed, with 10.1 % of respondents in Northern Italy having attended at least one event, compared to 7.4 % in the Centre-South.

Knowledge and perception of sustainability

The general level of knowledge about environmental sustainability among respondents was evaluated on a scale from 1 (Not at all) to 5 (Completely). The median response was 3 (2—3), indicating that most respondents assessed their knowledge as moderate (“Moderate”). However, a significant portion of respondents reported having only limited knowledge (“Limited”, 38.2 %) or no knowledge at all (4.2 %), while only a small percentage (11.0 %) considered themselves very knowledgeable (“High” or “Completely”).

A statistically significant association ($p < 0.05$) was found between

sustainability knowledge and participation in at least one session or presentation on the topic (Fig. 2a). Among those who had attended at least one sustainability-related event, the median knowledge level was 3 (3—3), while those who had never participated in such events had a median of 3 (2—3).

Geographical differences were also observed ($p < 0.05$), with respondents from Northern Italy reporting a higher sustainability knowledge level than those from the Centre-South. The median knowledge level in the North was 3 (2—3), while in the Centre-South, it was 2 (2—3) (Fig. 3).

The perceived impact of individuals, teams, and organizations on sustainability was analyzed across three levels, showing significant differences ($p < 0.05$) across all combinations. At the individual level, participants agreed on the influence of their own actions 4 (4—4). The team impact was perceived as slightly greater 4 (4—5). At the organizational level, respondents more strongly recognized the organization's influence on sustainability, with a median of 5 (4—5) (“strongly agree”). The strong correlation between levels ($r = 0.75$ between individual and team impact; $r = 0.67$ between team and organization) highlights their interconnection. Furthermore, the perception of organizational impact significantly varies ($p < 0.05$) between those working in an Institute for Scientific Research and Care (IRCCS) and those who do not. All Likert scale results for this section are presented in Fig. 2a.

Sustainable initiatives and measures in radiotherapy

The analysis revealed that 41.9 % of respondents reported the implementation of sustainability initiatives in radiotherapy centers, while 58.1 % indicated the absence of such measures. In particular, respondents from radiotherapy centers in the North were slightly more likely to adopt sustainable practices (43.2 %) compared to those in the Centre-South (38.2 %). In centers that had adopted sustainability initiatives, respondents demonstrated a statistically higher level of sustainability knowledge (median: 3 [2–5]) compared to those in centers without such initiatives (median: 3 [2–3]; $p < 0.05$). Among those who reported the presence of sustainability initiatives, the most commonly implemented measures were digitalization to reduce paper usage (67.5 %) and the adoption of eco-friendly operational protocols, such as reducing consumption and improving waste management (60 %). In contrast, the least frequently reported measures included collaborations with third-party organizations for sustainable transportation (13.8 %) and sustainability training courses for staff (17.5 %), as illustrated in Fig. 4.

In evaluating the level of agreement with four strategies to enhance sustainability in radiotherapy (Fig. 2b) –adopting protocols for optimized equipment use, continuous staff training, establishing dedicated sustainability teams, and signing agreements with external entities– a high level of consensus emerged, with a median score of 4 for all strategies. However, while equipment protocols, staff training, and agreements with external entities had an interquartile range of 4–5, the establishment of a dedicated sustainability team received a significantly lower score, with an interquartile range of 3–4 ($p < 0.05$).

Barriers and challenges

The perception of radiotherapy centers' willingness to adopt more sustainable practices in the future, assessed using a Likert scale, showed a median of 3 (2–3), indicating a moderate level of interest.

Geographical differences emerged, with respondents from Centre-South Italy reporting a significantly higher ($p < 0.05$) “moderate interest” (median 3) compared to those from Northern Italy, who showed “low interest” (median 2). Additionally, the perception of willingness to adopt sustainable practices was significantly higher ($p < 0.05$) among those working in centers that had already implemented sustainability initiatives (median 3) compared to those in centers that had not yet adopted any initiatives (median 2). The survey on the main barriers to

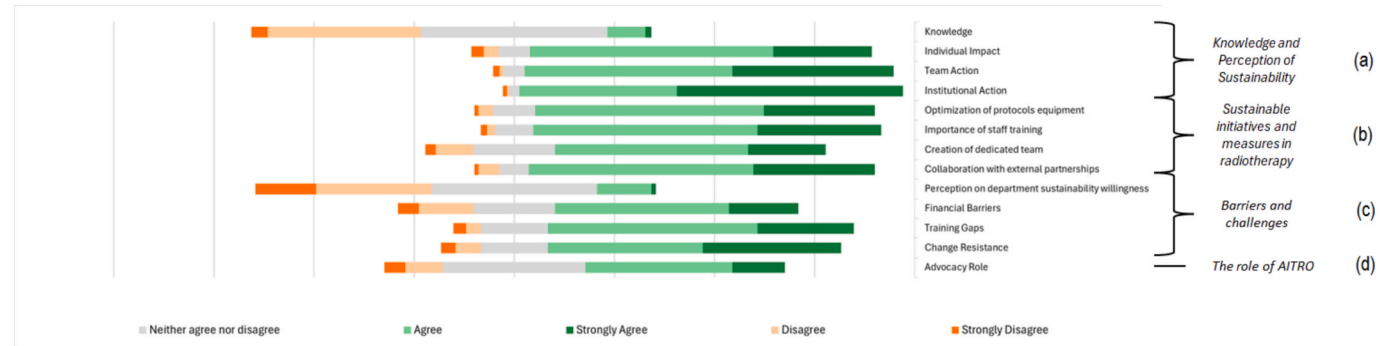


Fig. 2. Distribution of responses to Likert-scale items grouped into: (a) Knowledge and Perception of Sustainability, (b) Sustainable Initiatives and Measures in Radiotherapy, (c) Barriers and Challenges, and (d) The Role of AITRO.

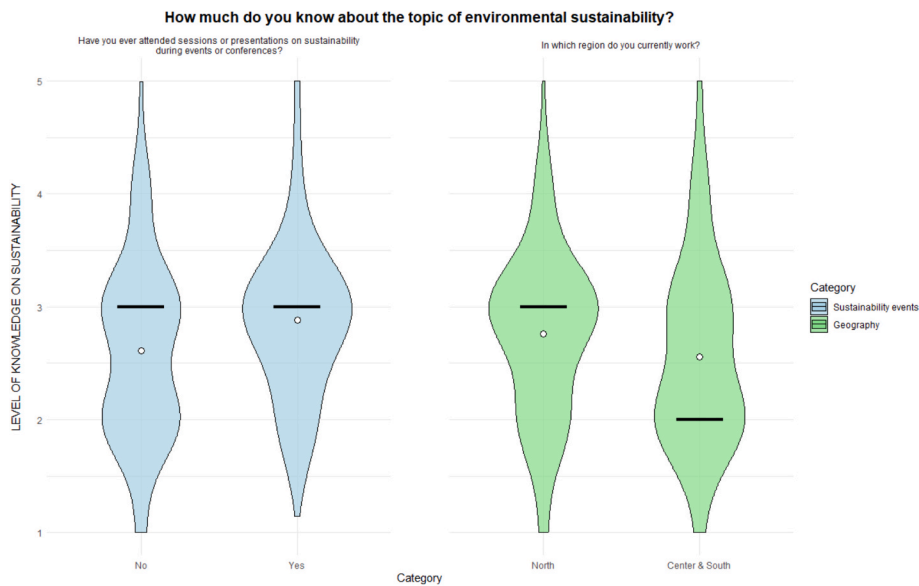


Fig. 3. Violin plot representing the distribution of sustainability knowledge levels (Likert scale 1–5) across two categorical variables: participation in sessions on sustainability during events ("Yes"/"No") and geographic area ("North"/"Center & South"). The black horizontal bars indicate the median values, while the white dots represent the means.



Fig. 4. Main sustainable initiatives reported from the surveys.

adopting sustainable practices in radiotherapy centers identified three perceived obstacles: lack of financial resources, insufficient staff training, and resistance to change (Fig. 2c). All barriers were considered relevant, with a median score of 4 (agree). However, lack of training (IQR: 4–4) and resistance to change (IQR: 3–5) were perceived as more critical ($p < 0.05$) compared to lack of financial resources (IQR: 3–4).

The role of AITRO

The role of professional national associations, such as AITRO, in promoting sustainability in radiotherapy was considered significant, with a median score of 3 (3–4), indicating a perceived importance between “Moderate” and “High” (Fig. 2d).

The main suggested contributions include organizing training courses (68.1 %), developing sustainability guidelines and protocols (67.5 %), and awareness campaigns (52.4 %), followed by professional networking (44.5 %), collaborations with institutions (43.5 %), and technical support and consultancy (39.8 %).

Demographic data

The survey collected demographic information to contextualize the findings. The majority of respondents were female (57.1 %) and male (41.9 %), with a median age of 38 (33–46) years. Regarding professional experience in radiotherapy, the largest group had 11–20 years of experience (28.8 %), followed by those with 1–5 years (25.1 %) and 6–10 years (24.6 %). A smaller percentage reported having less than one year of experience (5.8 %) or more than 20 years (14.7 %). Geographically, the highest number of respondents came from Lazio ($n = 37$), Lombardia ($n = 30$), and Emilia-Romagna ($n = 22$), with other notable contributions from Toscana ($n = 22$) and Puglia ($n = 14$). The survey showed a fairly even distribution across Italy, with 50.8 % of participants from the North and 49.2 % from the Centre/south. Educational background varied, with 45.5 % holding only a Bachelor's Degree, 26.2 % having obtained at least a Master's Degree.

Discussion

This study aimed to evaluate the perspectives of Italian RTTs on sustainability in Radiation Oncology through the completion of a survey. The data analysis revealed that although the topic of sustainability is becoming increasingly important, there is still a significant knowledge gap regarding its application in radiotherapy. This shows that the culture of sustainability is still a relatively new and complex challenge in this field, as reported in literature [28]. Although the responders to our survey were experienced RTTs—74.9 % had at least five years of experience—and had an age range of 33–46 years, typically associated with greater environmental awareness [29], our findings highlighted a moderate knowledge and awareness of sustainability practices. These results align with those reported in a recent review by Soares et al. [30], further emphasizing the limited familiarity with sustainability in the healthcare setting. These gaps in knowledge are consistent with findings at the European level, where diagnostic radiographers reported limited familiarity with methods to reduce environmental impact and energy consumption [31], as highlighted by the SAFE EU project and the EFRS position statement [32]. The participants' limited knowledge and awareness of sustainability underline the urgent need for targeted education and engagement, in line with the recommendation by Anudjio et al. [28], to promote development-specific training and research that enhance healthcare professionals' holistic assessment of the environmental impact of radiology and radiotherapy.

Engagement in sustainability discussions modestly improves self-reported understanding, but limited participation in training highlights the need to expand access and promote targeted education in radiotherapy. The findings reveal territorial and organizational factors influencing the diffusion of sustainability practices in Italy, with

significant North–South disparities suggesting that unequal access to initiatives may affect RTTs' self-perceived competence. This pattern is in line with broader analyses of Italy's healthcare system, which emphasize the effects of regional decentralization on policy capacity and healthcare delivery [33–35]. The analysis also revealed a statistically significant association ($p < 0.05$) between sustainability knowledge and workplace environment: RTTs working in centers that actively promote sustainability report higher levels of awareness (median knowledge score: 3 [2–5]). This supports the notion that proactive institutional cultures can foster better understanding [36]. Additionally, a significant difference ($p < 0.05$) exists between RTTs employed in IRCCS and RTTs in other settings, suggesting that research-oriented institutions may play a strategic role in advancing sustainability mindsets, as reported in literature [37]. Key contributors to the environmental footprint of radiotherapy departments include high energy consumption, extensive use of clinical consumables, and travel-related emissions from both staff and patients [28,38]. In parallel, interest from radiotherapy companies to report annual reductions in carbon emissions is also reported, and sustainable linear accelerators have shown lower energy consumption compared to standard models [39]. In line with international evidence, strategies such as hypofractionation, telemedicine, reduction of SF6 leakage, and optimized patient transport are recognized as high-impact measures to mitigate emissions [12,20]. The recently published GRF by the UK Radiotherapy Board systematizes these actions into bronze, silver, and gold levels, ranging from low-threshold measures (e.g. waste reduction, paperless processes) to more complex interventions (e.g. hypofractionation, sustainable procurement, and integration of renewable energy) [21].

Consistent with bronze-level recommendations on reducing paper usage through digital processes, 28.3 % of respondents of our survey reported digitalization initiatives, suggesting that Italian RTTs are mainly engaged in low-threshold, easily implementable actions [21]. In the same category of basic measures, 8.4 % indicated the use of educational infographics to promote awareness among staff and patients [21]. About one quarter (25.1 %) reported the adoption of eco-friendly protocols, corresponding to basic and intermediate measures such as turning off linear accelerators when not in use, reviewing operating hours to improve efficiency, and introducing reusable or recyclable items [21]. By contrast, only 7.3 % of RTTs reported dedicated training on sustainability, highlighting a major gap compared with recommended silver-level actions such as staff awareness initiatives, integration into induction, and regular communication [21]. Finally, green transport for patients and staff was mentioned by only 5.8 % of respondents, whereas higher-level measures include promoting teleconsultations, reducing patient journeys, and encouraging active or public transport, as described among the gold-level actions of the GRF [21]. Patient travel has consistently been identified as one of the main contributors to the carbon footprint of radiotherapy, and models such as satellite centers have been proposed to mitigate this impact [40–42]. Where sustainability initiatives exist, reported investments focus primarily on digitalization and the use of eco-friendly operating protocols (bronze level), while smaller investments are made in staff sustainability training and third-party agreements for sustainable staff transportation (silver and gold levels). Building a sustainable radiotherapy model requires systemic change through multi-level collaboration, with respondents highlighting that team-based efforts enhance effectiveness, while organizational policies and structural initiatives act as key drivers of change.

Overall, the importance of management involvement as a catalyst for promoting sustainability is clearly emphasized [1,43]. The statistically significant difference between centers that adopted sustainability initiatives and those centers that have not shown that working in an environment that actively promotes sustainability can improve awareness and understanding of the issue among professionals. Our survey confirms what has already emerged in the literature, namely the gap between the cultural principles of sustainability and their effective

translation into daily practice. Many RTTs associate sustainability mainly with simple and fragmented actions rather than with an integrated clinical mindset. This finding reflects what is highlighted by the international framework, which identifies the establishment of a widespread sustainability culture as a fundamental prerequisite for structural change [44]. In line with this evidence, the 2024 Lancet Countdown Europe report also emphasizes that building climate-resilient healthcare requires a cultural and systemic shift, moving beyond individual actions to collective responsibility [45]. In line with this broader perspective, recent analyses show that international radiotherapy conferences also generate substantial travel-related emissions, indicating that sustainability efforts must extend beyond clinical practice to the wider professional community [46].

This study underlines the central role of national professional organizations such as AITRO in promoting sustainability in radiotherapy. These organizations can significantly enhance the ability of radiotherapy departments to address environmental challenges in a structured and measurable way. Participants highlighted the need for targeted training programs and standardized guidelines — key areas in which national societies can invest to promote a culture of environmental responsibility. Strengthening these efforts could significantly support the successful implementation and wider adoption of sustainable practices across radiotherapy centers. The integration of sustainability into radiotherapy is not only an ethical imperative but also a strategic investment. It aligns quality cancer care with global commitments to climate resilience and sustainable development. Based on our findings, we propose three key recommendations for AITRO:

- Promote dedicated training programs to increase RTTs' awareness and competencies in sustainability.
- Develop and disseminate strategic guidance to support the adoption of environmentally responsible practices in radiotherapy departments.
- Facilitate data collection and benchmarking across centers to monitor sustainability initiatives and identify areas for improvement.

Limitations

A total of 191 responses were collected, about 10 % of Italian RTTs, mainly reached through AITRO social channels and congresses. Furthermore, the questionnaire did not undergo formal validation procedures such as calculation of the Content Validity Index (CVI) or Cronbach's alpha, which represents an additional methodological limitation. Most of the responses came from regions with a high number of AITRO members; moreover, the age distribution of the sample may not be representative of the general RTT population, as younger RTTs are more easily reached through social media channels and congress participation. The study design was developed by the AITRO Scientific Committee through dedicated focus group, taking into account innovative topics, especially among RTTs at a global level, and insufficient results in literature. As the questionnaire was developed and disseminated by the AITRO Scientific Committee, the results may reflect the perspectives of RTTs closer to the association, introducing a potential selection and content bias. The survey was conducted exclusively in Italy and in Italian language, which increases the regional relevance of AITRO, but also represents a limitation for a broader international understanding.

To improve the consistency and generalizability of the study, future research should aim to include other scientific associations in Italy, in order to enhance representativeness across the various professionals working in radiotherapy, including radiation oncologists, medical physicists, nurses, psychologists, and support staff. Future surveys should also take into account newly emerging initiatives to capture a broader spectrum of sustainable actions, and should define existing

initiatives in a more quantitative way to allow better evaluation of their scope and impact.

Conclusion

This national survey reveals that the level of knowledge and participation in sustainability-related training among Italian RTTs is moderate. The findings underscore the need for a clearly defined and research-backed strategy to integrate sustainability into radiotherapy practice. To effectively address the identified barriers, it is essential to design and implement specific educational programs, to improve interprofessional awareness and to foster institutional commitment. Professional organizations, such as AITRO, are able to play a key role in supporting this change. By developing educational pathways, disseminating best practices and advocating for sustainability policies. Looking to the future, international surveys will be needed to provide a broader perspective and to strengthen cooperation with international scientific societies and stakeholders. Better coordination on possible initiatives and strategies is certainly encouraged.

CRediT authorship contribution statement

Claudio Votta: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Formal analysis, Project administration. **Andrea Lastrucci:** Validation, Visualization, Writing – original draft, Formal analysis. **Nicola Iosca:** Validation, Visualization, Writing – original draft, Formal analysis. **Davide Bassani:** Data curation, Visualization, Writing – original draft. **Lucrezia Bernabucci:** Data curation, Visualization, Writing – review & editing. **Mattia Bertolini:** Validation, Visualization, Writing – review & editing. **Carmela Galdieri:** Data curation, Visualization, Writing – review & editing. **Danilo Pasini:** Validation, Visualization, Writing – review & editing. **Valerio Pisoni:** Data curation, Visualization, Writing – review & editing. **Aurora Zucca:** Validation, Visualization, Writing – review & editing. **Daniele Lambertini:** Supervision, Validation, Visualization, Writing – review & editing. **Patrizia Cornacchione:** Supervision, Validation, Visualization, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.tipsro.2025.100360>.

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