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INTEGRATING ERGONOMIC DESIGN AND SUSTAINABILITY ASSESSMENT: A SYSTEMATIC REVIEW OF HUMAN-CENTRED APPROACHES IN SUSTAINABLE PRODUCT DEVELOPMENT

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ABSTRACT
Sustainable product development has emerged as an important issue of concern to industries that seek to ensure that the environmental effects are minimized without compromising the product use and functionality. Despite the fact that the ergonomic design and sustainability assessment are widely acknowledged as the key elements of the contemporary product development, the studies that deal with the integration of the aforementioned aspects are still disjointed. This paper will provide a systematic literature review on the application of principles of ergonomic design and sustainability assessment techniques in product development study. The review is conducted based on the PRISMA protocol to provide a transparency and rigour of the methodology. The major academic databases, such as Scopus, Web of science, ScienceDirect and Google Scholar, were searched to identify relevant studies published between 2000 and 2025. The results show that the majority of studies consider ergonomics and sustainability as two different areas, and ergonomic studies have been based on usability and human performance. Conversely, sustainability studies focus on the assessment of environmental impact with the help of such tools as life cycle assessment. Nevertheless, there is increasing evidence on the significance of human-centred design to enhance sustainability performance through user behavior, product life and lifecycle performance. According to the review results, this paper suggests a synthesized conceptual framework, integrating inputs of user-centred design, ergonomic assessment techniques, and sustainability assessment measures in an iterative product development process to facilitate more holistic sustainable product innovation.

KEYWORDS: Ergonomic design; Sustainable product development; Human-centered design; Sustainability assessment; Life cycle assessment; Human factors engineering; Systematic literature review.

INTRODUCTION

1.1 Background of Sustainable Product Development

The development of sustainable products has emerged as a burning issue of concern to industries that are confronted with mounting environmental issues, regulatory demands and societal demands of responsible production and consumption. The problems of resource depletion, greenhouse gas emissions and waste generation have been exacerbated by industrial growth and technological progress, which prompts organizations to implement sustainability-focused design solutions that can decrease the environmental impact throughout the product lifecycle (Delaney et al., 2022; Tukker, 2015).

This strategy incorporates the environmental, economic and social factors into the product design and innovation, which is consistent with the principles of sustainable development that focus on satisfying the current generation without endangering the future generation (Hariram et al., 2023). Practically, sustainability is tackled with the help of eco-design approaches, the principles of the circular economy and the lifecycle thinking that considers the effects of extracting materials to end-of-life management (Charter & Tischner, 2017; Bocken et al., 2016).

Besides material efficiency and production processes, sustainability performance is also determined by the way users engage with the products during their lifecycles. This has led to the realization of the interaction between human products as a significant constituent of sustainable product innovation.

1.2 Role of Ergonomic Design in Product Development

Products are designed in such a way that they are in tandem with human capability, limitations and behavioral characteristics. Ergonomics is also referred to as human factors engineering and is concerned with ensuring that the interactions between humans and the technological systems are optimized to enhance usability, safety and system performance (Trstenjak et al., 2025).

Ergonomics in product development is used to design products that can be more comfortable to the user, less physically straining, and efficient in their operation. The human-centred design methodologies also focus on the knowledge of the user needs, including user research and usability testing (Gottgens et al., 2021). As the digital technologies become more complex, ergonomic design also embraces cognitive ergonomics and interaction design to solve the problem of mental workload and human-technology interaction (Hilmi et al., 2024).

1.3 Need for Integrating Ergonomics and Sustainability

Although the idea of sustainable product development has gained increasing popularity, most of the sustainability assessment frameworks are mainly concerned with environmental indicators including energy consumption, carbon emissions and the efficiency of materials. Although these indicators are significant in assessing the environmental performance, they tend to ignore the role of human factor and user behavior in determining the sustainability performance (Bennett et al., 2017; El Agamy AbdelKader, 2023). The behavior of the user at the stage of using the product can have a considerable influence on the environmental impact. The burdens to the environment can be contributed by poor operation, ineffective maintenance, or timely replacement even after the use of sustainable materials in the design of the products. These issues can be overcome by ergonomic design, which enhances usability and facilitates users to adopt more efficient behaviors with the help of intuitive interfaces and feedback (Lockton et al., 2013).

Combining ergonomic design and sustainability evaluation is hence a more holistic method of product development based on two important aspects; the environmental performance and the interaction between the human and the product.

1.4 Research Gap

Whereas both ergonomics and sustainability are significant factors in product development, little research has been done on how the two concepts can be combined. The main aim of ergonomics research is to enhance usability, safety and human performance whilst the main aim of sustainability research is to assess environmental effects throughout product life cycles. The current sustainability assessment techniques offer useful information on the environmental performance but seldom include human-based aspects including usability and user behavior. Equally, ergonomic design models tend to focus on the user-experience without the systematic approach to the aspects of environmental sustainability. As a result, few studies have been able to synthesize the role of ergonomic design principles in sustainable product development. A literature review is thus required to be systematic to bring together the existing literature and also find ways of incorporating ergonomics and sustainability in product design.

Research Objectives

- To address the revealed research gap, the proposed study will conduct a systematic literature review that will cover literature covering the topic of integrating ergonomic design and sustainability assessment into product development. The research questions of this work are:
- To investigate the use of ergonomic design in the study of sustainable product development.
- To examine the sustainability assessment techniques applied in product design research.
- To determine human-centred design solutions to sustainable innovation.
- To suggest a conceptual framework that would combine ergonomic design and sustainability assessment.

1.6 Research Questions

According to these objectives, the research questions of the study are as follows:

- RQ1: What has been done concerning the use of ergonomic design in sustainable product development studies?
- RQ2: Which sustainability assessment tools are applied in ergonomic product design research?
- RQ3: What is the human-centred design practices that facilitate product development sustainability?
- RQ4: What can be done to incorporate ergonomics and sustainability assessment into one system of sustainable product development?

1.7 Structure of the Paper

The rest of this paper will be structured in the following way. Section 2 provides the theoretical background of the ergonomic design, human-centred design and sustainability assessment techniques. The systematic review methodology is outlined in section 3. Section 4 is the descriptive analysis of the reviewed literature. In the sections 5 and 6, the authors consider the ergonomic strategies and sustainability evaluation techniques in the design of products. Section 7 covers the combination of ergonomics and sustainability. Section 8 gives the discussion and research gaps and Section 9 gives a proposal of a conceptual framework that incorporates ergonomics and sustainability assessment. Lastly, Sections 10-12 provide practical implications, study limitations and conclusions.

2. THEORETICAL BACKGROUND

2.1 Ergonomic Design in Product Development

The ergonomic design is also significant in product development since it helps to make products compatible with human abilities, constraints and behavioral attributes. Ergonomics or human factors engineering is the study of human technology interrelation that aims at enhancing usability, safety and system performance (Dul and Weerdmeester, 2008). Ergonomic principles are applied in product design to minimize physical load, operational error, and increase user comfort and efficiency.

Ergonomics is broadly categorized into three areas namely physical, cognitive and organizational ergonomics. Physical ergonomics deals with anthropometric and biomechanical aspects of the human body that impact product interaction like posture and anthropometry (Dianat et al., 2018). Cognitive ergonomics is concerned with the mental processes and perception, attention and decision-making during human-technology interaction (Wickens et al., 2015). Organizational ergonomics studies the interrelation of people, technologies and work systems to enhance cooperation and system performance (Gualtieri et al., 2020). Collectively, these areas are involved in the enhancement of usability, productivity, and user well-being in product design (Dhiman et al., 2023).

2.2 Human-Centred Design Principles

One such strategy is human-centred design (HCD), a strategy that focuses on the user needs, capabilities and experiences during the product development process. It tries to create solutions that fit the reality of the user behavior and usage situations, thus enhancing usability and the overall product experience (Moustafa, 2023; Harte et al., 2017).
User-centred design (UCD) is a popular HCD approach that involves user requirements and feedback with the help of interviews, usability tests, and observational studies (ISO 9241-210). Design approaches that are participatory and inclusive also contribute to the development of the product through engaging users in the design process and making the products accessible to a wide range of users, which promotes the social sustainability.

2.3 Sustainability in Product Development

The growing environmental issues and resource limitations have made sustainability an important issue in product development. Sustainable product development is an idea that aims to balance the environmental protection, social well-being and economic performance during the product lifecycle and can be described through the concept of the triple bottom line (Nogueira et al., 2023; Munoz-Pascual et al., 2019). Environmental sustainability is aimed at minimizing the effects of the product design, manufacturing, use and disposal, which is achieved by using eco-design, energy efficient technologies and recyclable materials (El Agamy Abdel Kader, 2023). Life cycle thinking also promotes sustainability through environmental analysis of extracting the raw materials to end-of-life management.
The social sustainability is concerned with the well-being, safety and accessibility of the users as opposed to economic sustainability which is concerned with long term product value, resource efficiency, durability and reduction of the costs of life cycle.

2.4 Sustainability Assessment Methods

A number of analytical tools have been created to measure sustainability performance in product development. One of the most popular models of evaluating the environmental impact over the whole product lifecycle is life cycle assessment (LCA). LCA allows designers to assess the environmental impact burdens related to the extraction of materials, manufacturing, consumption and disposal of the product (Joshi and Gupta, 2019).
Other complementary assessment tools are carbon footprint analysis that quantifies greenhouse gas emissions linked to product systems and material flow analysis (MFA) which analyses the flow of materials in production systems to find opportunities to optimize resources and recycle them (Joshi and Gupta, 2019). The eco-design tools also assist in the integration of sustainability where the designers are guided on the choice of materials that are more eco-friendly and enhancing product recyclability.

2.5 Linking Ergonomics and Sustainability

The connection between Ergonomics and Sustainability is as follows.
Combining sustainability with ergonomics has become a significant research orientation in sustainable product development. Although the sustainability study frequently addresses the environmental performance, human-product relations also play a crucial role in the lifecycle sustainability results (Taddese et al., 2020).
Energy consumption, maintenance, and product lifespan may be influenced by the behavior of the users during use. Inefficient operation or premature replacement may be caused by poor usability, which enhances environmental effects (Delaney et al., 2022). Ergonomics can help solve these issues by making them more usable and promoting more efficient usage patterns. Intuitive and comfortable products will be retained longer, which contributes to sustainable consumption. As such, a combination of ergonomics and sustainability evaluation is an effective way of enhancing the well-being of users and environmental performance.

Figure 1. Conceptual overview of ergonomics, human-centred design, and sustainability assessment in sustainable product development

3. METHODOLOGY

3.1 Research Design

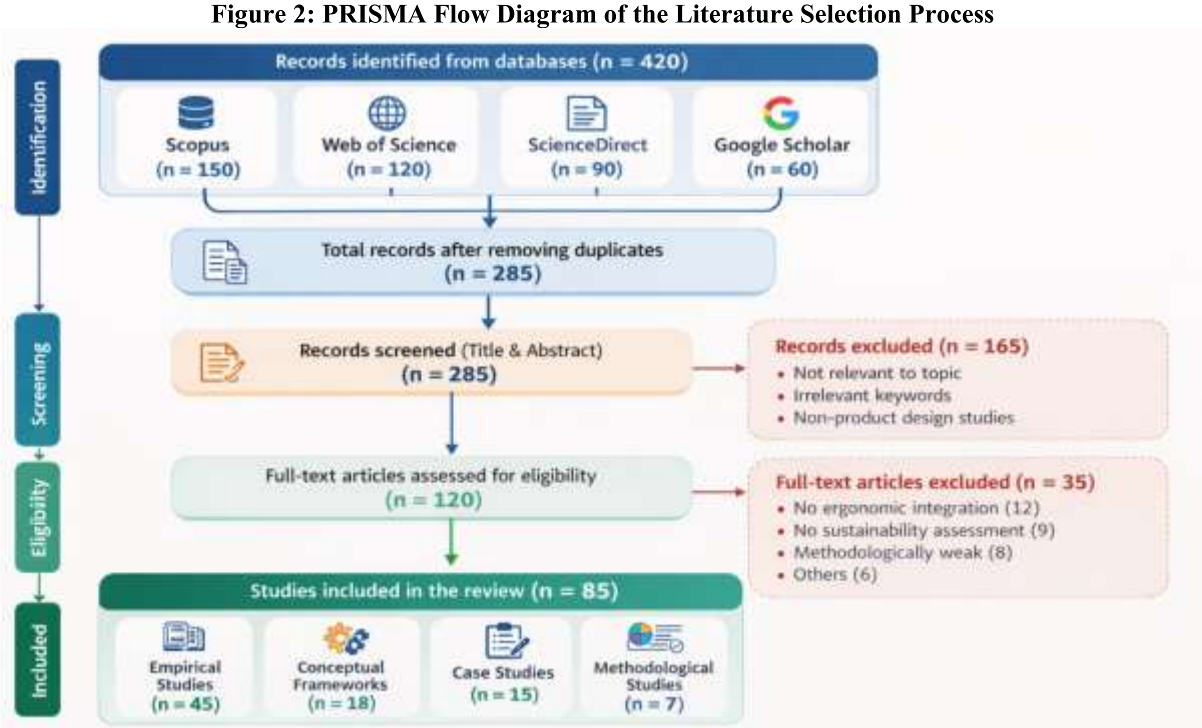
This paper will use systematic literature review to analyses how ergonomic design and sustainability assessment are integrated in product development. Systematic reviews are also a structured and transparent method of finding, processing and interpreting existing research, which increases the rigour of the methodology and reduces the potential bias (Shaheen et al., 2023).

The approach is particularly appropriate to interdisciplinary problems such as sustainable product development where the research spans disciplines of ergonomics, product design, sustainability engineering, and human-computer interaction. By synthesizing the findings of these areas, the review provides a broad understanding of how ergonomic principles can be used to design products that are sustainable in nature.

3.2 Review Protocol

The review is based on the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) to guarantee the transparency and rigour of the methodology (Page et al., 2021). The PRISMA framework divides the review process into four key steps, namely, identification, screening, assessment of eligibility and inclusion of the relevant studies. The stages enable the researcher to narrow down a vast number of publications into a narrow set of research that can answer the research questions. The general process of study selection can be summarized with the help of a PRISMA flow diagram (Figure 2).

Figure 2: PRISMA Flow Diagram of the Literature Selection Process



3.3 Database Selection and Search Strategy

To make sure that the literature coverage is complete, a number of academic databases were studied, such as Scopus, Web of Science, ScienceDirect and Google Scholar. Scopus and Web of Science were chosen because they have a wide range of peer-reviewed journals, whereas ScienceDirect offered access to engineering and sustainability publications. Google Scholar was utilized as a secondary source to find more related studies.

A systematic search strategy with Boolean operators and keywords on the subject of ergonomics and sustainability were utilized. Such keywords as ergonomic design AND sustainable product design, human-centred design AND sustainability, ergonomics AND life cycle assessment were used as an example of search strings. The search included articles published since 2000 up to 2025, which is the period of the increase of research on sustainable product development and human-centred design (Geissdoerfer et al., 2017). Relevancy was achieved by searching by titles, abstracts and keywords.

3.4 Search Strategy

A systematic search plan was made to find literature on product development ergonomic design and sustainability. Keywords and Boolean operators were applied regarding the ergonomics, human-centred design, and sustainability assessment. Such keywords as ergonomic design AND sustainable product design, human-centred design AND sustainability, ergonomics AND life cycle assessment were used as an example of search strings. The search was conducted on publications published between 2000 and 2025, which is why it is possible to speak about the growth of research on sustainable product development and human-centred design (Geissdoerfer et al., 2017). The process of searching was carried out by titles, abstracts and keywords to make sure that the chosen studies were relevant.

3.4 Inclusion and Exclusion Criteria

A predetermined inclusion and exclusion criteria were used to make sure that the literature chosen was relevant and good. The inclusion criteria were that the studies had to be published in peer-reviewed journals and discuss the ergonomic design, human-centred design, or human factors in the product development and also discuss the sustainability aspects, including environmental impacts, lifecycle assessment, or sustainable design strategies. The studies were filtered out based on the following criteria: not written in English, no available full-text articles, or editorials, book reviews, or other non-peer-reviewed articles. The review also excluded articles that were not related to the product design or sustainable development.

3.5 Study Selection Process

The PRISMA framework was used in the study selection. During the identification phase, the search of the selected databases was performed using predefined search strings, and the duplication of the records was eliminated. In screening, titles and abstracts were looked into to determine the relevance of the same to the ergonomic design and sustainability in product development.

During the eligibility phase, full-text articles were screened on the inclusion criteria. The last inclusion step led to the choice of the studies to be analyzed in detail. The general process of selection can be described by the PRISMA flow diagram (Figure 2), which indicates the number of identified, screened, excluded and included articles in the review.

3.6 Data Extraction and Quality Assessment

After the selection of the studies, a systematic data mining procedure was applied to gather the main details of each article such as author and year, study goals, methodology, ergonomic design strategies, sustainability evaluation techniques, area of application and main conclusions. The obtained data were presented in a structured dataset to enable a comparative study and determine research trends on the integration of ergonomics and sustainability. Quality assessment was also done on the basis of criteria that were adjusted to Tranfield et al., (2003). Research design was tested; data collection and analysis method was appropriate and relevant to the research objectives. During the synthesis and discussion phases, studies that had high methodological rigour and were making clear contributions were given priority.

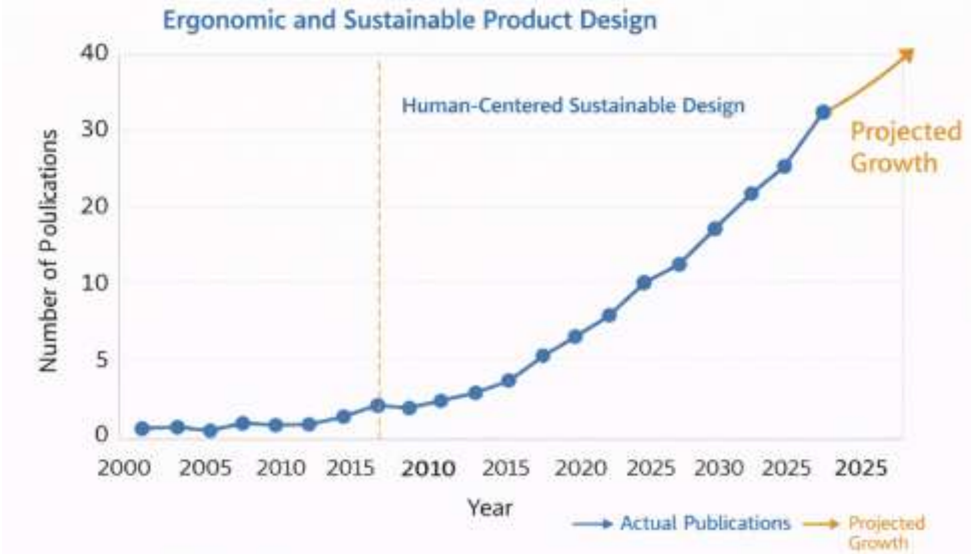
4. DESCRIPTIVE ANALYSIS OF THE LITERATURE

This section gives a descriptive summary of the studies that were incorporated in the systematic review. Systematic reviews often involve descriptive analysis to determine the trends in research, thematic areas and methodological patterns in a field (Snyder, 2019; Tranfield et al., 2003). The review of the trends in publications, the areas of research, geographic allocation and the application of research in the industry can be used to demonstrate how ergonomic design and sustainability integration research has developed in product development. The connection between human-centred design and sustainability assessment is also a topic in this analysis, emphasizing how various research communities approach the topic (Rossi & Attaianese, 2023).

4.1 Publication Trends Over Time

The patterns of publications show that the number of studies that consider the combination of ergonomics and sustainability into product development is constantly growing during the last twenty years. At the beginning of the 2000s, the study of ergonomic design and sustainable product development was primarily independent, as studies of sustainability were primarily about eco-design strategies, material efficiency and lifecycle thinking (Luttropp & Lagerstedt, 2006; Charter & Tischner, 2017).

Figure 3. Publication trend in research on ergonomics and sustainable product development (2000–2025).



Since about 2010, studies have begun to focus on the importance of human-centred design in sustainable product development with an appreciation of the fact that user behavior and human-product interactions affect the lifecycle sustainability outcomes (Borthwick et al., 2022; Gomide et al., 2024). Later, the increased interest in the principles of the circular economy and lifecycle sustainability assessment, has further enhanced the incorporation of ergonomic design in sustainable product innovation (Bocken et al., 2016; Geissdoerfer et al., 2017).

4.2 Distribution by Journal and Research Domain

The studies reviewed represent a wide variety of academic fields, which is due to the interdisciplinary character of research into the ergonomic design and sustainable product development. They are usually published in journals in the field of industrial engineering, product design, sustainability science and human-computer interaction. Journals that are sustainability-oriented are characterized by the lifecycle assessment, eco-design and strategies of the circular economy, whereas journals of engineering and design are characterized by the ergonomic approach and usability analysis (Bocken et al., 2016; Geissdoerfer et al., 2017).

Some of the major journals in this area are the Journal of Cleaner Production, Applied Ergonomics and Sustainable Production and Consumption. This distribution reflects the increased significance of interdisciplinary cooperation in the field of ergonomics, design engineering and sustainability research (Zink, 2014; Hauschild et al., 2018).

4.3 Geographic Distribution of Studies

The geographical distribution of the studies indicates that the study on ergonomic design and sustainability integration is focused in Europe, North America and East Asia where there is a good academic institution, advanced industry and sustainability policies. The European countries have been especially engaged in the field of sustainable product design, with Germany, Sweden and the Netherlands being the most active ones and the European Union initiatives that promote resource efficiency and circular economy strategies contribute to this trend (Silander, 2019; Geissdoerfer et al., 2017).

Figure 4. Geographic distribution of studies on ergonomic design and sustainable product development.

The United States and Canada, in particular, have also played a significant part, and the research on the topic is regularly aimed at the combination of human factors engineering with sustainability assessment (Karwowski, 2005; Thatcher et al., 2019). Most recently, Asian nations, such as China, Japan, and South Korea, have become more contributing countries because of the accelerating industrialization process and environmental issues (Bocken et al., 2016; Hauschild et al., 2018).

4.4 Industry Application Areas

The literature reviewed indicates that the ergonomic design and sustainability concepts are implemented in various industrial sectors. Ergonomic interventions in manufacturing enhance efficiency and safety of workers, whereas sustainability initiatives aim at minimizing the use of resources and waste (Zink, 2014; Allwood, 2012).

Ergonomics and sustainability will also be essential in healthcare product design to be usable, safe and accessible with minimal environmental impacts (Dul & Weerdmeester, 2008; Charter & Tischner, 2017). Ergonomic interface design can be used to improve the user experience in consumer electronics, and sustainability strategies can be used to deal with electronic waste and product lifecycle (Bocken et al., 2016; Geissdoerfer et al., 2017).

Equally, the automotive sector integrates ergonomic design of vehicles with sustainability policies through lightweight materials and energy-saving technologies to enhance the environmental performance of the lifecycle (Hauschild et al., 2018; Tukker, 2015).

4.5 Research Methodologies Used

The research methodologies used in the reviewed studies are different, and this interdisciplinary character of ergonomic and sustainability research is explained. Ordinary methods are the empirical studies, the case study, and building of conceptual frameworks. Empirical studies usually include experimental assessments, usability studies and quantitative research studies that investigate the correlations between ergonomic design characteristics and sustainability results

(Karwowski, 2005; Wickens et al., 2015).
Case studies examine how ergonomic and sustainable design practices are applied in the real world in industries (Erdinc & Yeow, 2011; Zink, 2014). Besides that, the conceptual research suggests the frameworks of the connection between the principles of human-centred design and sustainability assessment techniques, as well as the impact of ergonomic design on the user behavior and the performance of the product lifecycle (Bocken et al., 2016; Geissdoerfer et al., 2017; Tukker, 2015).

Table 1. Summary of Selected Studies on Ergonomic Design and Sustainability in Product Development

Author(s)	Year	Industry / Application	Ergonomic Approach	Sustainability Method	Key Contribution
Luttropp & Lagerstedt	2006	Product Design	Design for usability	Eco-design principles	Introduced eco-design guidelines for sustainable product development.
Erdinc & Yeow	2011	Consumer Products	Human-centred design	Sustainable design strategies	Highlighted the role of user behaviour in influencing product sustainability.
Karwowski	2005	Industrial Systems	Human factors engineering	Sustainable system design	Emphasized the importance of ergonomics in improving system efficiency and safety.
Dul & Weerdmeester	2008	Engineering Design	Physical and cognitive ergonomics	Sustainable work design	Provided foundational principles of ergonomics applied to product and workplace design.
Silander	2019	Product & Interaction Design	User-centered design	Sustainable user interaction	Demonstrated how intuitive design improves product usability and adoption.
Zink	2014	Manufacturing Systems	Workplace ergonomics	Sustainable work systems	Established connections between ergonomics and sustainability in production systems.
Lockton	2013	Consumer Technologies	Behavioral design	Sustainable consumption strategies	Proposed design interventions to influence sustainable user behaviour.
Geissdoerfer et al.	2017	Industrial Systems	Design thinking	Circular economy framework	Developed a circular economy model linking sustainability and product lifecycle design.
Bocken et al.	2016	Product Innovation	User-centered innovation	Circular product design	Identified sustainable business models and product innovation strategies.
Hauschild et al.	2018	Product Development	Design evaluation methods	Life Cycle Assessment (LCA)	Provided frameworks for assessing environmental impacts in product design.
Brunner & Rechberger	2016	Industrial Systems	System analysis	Material Flow Analysis	Introduced material flow analysis for resource efficiency and sustainability.
Wickens et al.,	2015	Human-Computer Interaction	Cognitive ergonomics	Sustainable interaction design	Examined how cognitive workload affects human–technology interaction.
Wilson	2014	Organizational Systems	Organizational ergonomics	Sustainable work organization	Discussed the role of sociotechnical systems in sustainable work environments.
Charter & Tischner	2017	Product Innovation	User-centered product design	Sustainable product strategies	Provided strategies for integrating sustainability into product design processes.
Dianat et al.,	2018	Product & Workplace Design	Anthropometric analysis	Ergonomic design standards	Highlighted the use of anthropometric data in product and workplace design.
Tukker	2015	Industrial Systems	Service-oriented design	Product-service systems	Demonstrated how product-service systems support sustainable consumption.

Allwood et al.,	2012	Manufacturing	Process ergonomics	Sustainable manufacturing	Explored material efficiency and sustainable manufacturing technologies.
Snyder	2019	Research Methodology	Literature review methods	Systematic review approaches	Provided methodological guidance for conducting systematic reviews.
Page et al.,	2021	Research Methodology	Evidence synthesis	PRISMA framework	Established updated guidelines for transparent, systematic literature reviews.
Borrego et al.,	2014	Research Methodology	Systematic review methods	Evidence-based research	Provided guidelines for conducting systematic literature reviews in engineering.

Table 1 presents the main studies that were incorporated in the review and that include the industry application, ergonomic methods, sustainability assessment methods, and the significant contributions of the research.

5. ERGONOMIC APPROACHES IN SUSTAINABLE PRODUCT DEVELOPMENT

The inclusion of ergonomic concepts in the development of sustainable products has received a growing interest as the human-focused approaches are identified as a key factor in meeting the sustainability goals. Ergonomics is aimed at creating products that match human capacity and behavior hence enhancing usability, safety and user satisfaction (Dul and Weerdmeester, 2008; Karwowski, 2005). Ergonomic design may be used together with sustainability to improve product efficiency, increase product life and promote responsible user behavior (Zink, 2014; Bocken et al., 2016).

Despite the fact that the indicators of environmental sustainability are mostly related with the energy consumption and material efficiency, recent studies show the importance of human-product relationships in defining the lifecycle sustainability outcomes (Taddese et al., 2020; Geissdoerfer et al., 2017). Products that are hard to maintain/use may lead to inefficient operation or replacement. By applying ergonomic principles to the design of products, it is thus possible to enhance environmental performance and user well-being (Hasanain, 2024; Hauschild et al., 2018).

5.1 Human-Centered Design Strategies

Human-centred design (HCD) is a popular practice to consider the ergonomic principles in product development by paying attention to user needs, behaviors and use situations (Norman, 2013; ISO 9241-210). Designers could gain a deeper insight into how users interact and create products that facilitate sustainable usage behaviors through various techniques, including usability testing, interviews and participatory design (Issa and Isaias, 2022).

Iterative design processes allow designers to develop product concepts by assessing and receiving feedback. The usability issues may be detected early enough to minimize the errors in design and cut down on the amount of material that is wasted in the process of development (Karwowski, 2005; Luttropp & Lagerstedt, 2006). Moreover, the design methods of inclusion and participation can be used to make products affordable to a wide range of users, which contributes to social sustainability and the durability of products (Charter & Tischner, 2017).

5.2 User Experience and Sustainability

User experience (UX) plays a significant role in the interaction of people with products and technologies. The positive UX is able to enhance the acceptance of the product, decrease the number of errors in operations and promote the further use of products, thus, ensuring the lifecycle sustainability (Peruzzini and Pellicciari, 2018; Ferreira et al., 2025). Improperly developed interfaces can result into ineffective functioning and higher energy usage, but well-developed interfaces, easy to understand feedback and simplified controls can help users make more sustainable decisions. The responsible consumption is also encouraged by design interventions like energy displays and behavioral nudges (Lockton et al., 2013; Bocken et al., 2016; Geissdoerfer et al., 2017).

5.3 Ergonomics Across Product Lifecycle Phases

Ergonomics influences the sustainability operations at the product lifecycle, including design, manufacturing, usage and end-of-life management (Luttropp and Lagerstedt, 2006; Hauschild et al., 2018). In the design phase, preliminary decisions regarding the user requirements, anthropometric fit, and user interface have a significant impact on the product performance and environmental impact (Dianat et al., 2018; Karwowski, 2005). The design tools used in digital design like digital human modelling allow the designer to test the interaction between humans and products and detect areas of usability problems prior to physical prototyping (Dul & Weerdmeester, 2008).

During the manufacturing stage, the ergonomic intervention is aimed at the design of the workstations, safety of the workers and elimination of repetitive activities. Ergonomically optimised production systems are able to enhance productivity and minimize injuries and production errors, which will lead to resource efficiency (Zink, 2014; Allwood et al., 2012).

The usage stage can usually affect the environmental performance the most since the user behavior directly impacts the energy usage and the product life (Shi et al., 2022). Easy to use interfaces that are easy to use and ergonomic can promote the efficient use of products and minimize energy use (Lockton et al., 2013).

Lastly, during the end-of-life stage, the ergonomic design can also facilitate the sustainable strategy of repair, disassembling, and recycling. The product lifespan is enhanced due to modular product architecture and design, supporting dismantling and maintenance of products, which promotes the use of the circular economy (Geissdoerfer et al., 2017; Bocken et al., 2016).

Figure 5: Ergonomic considerations across product lifecycle phases

6. SUSTAINABILITY ASSESSMENT IN PRODUCT DESIGN

Sustainability assessment is important in influencing the product development to be environmentally responsible. Increasing environmental awareness and legal demands have stimulated designers to incorporate sustainability in the product lifecycle (Hauschild et al., 2018; Tukker, 2015). The frameworks assist in assessing the environmental performance, determining hotspots of lifecycle impacts and aid in decision-making when designing a product (Geissdoerfer et al., 2017; Bocken et al., 2016). Sustainability assessment also supports the practice of circular economy by promoting the efficiency of resources, durability of products, and recyclability (Geissdoerfer et al., 2017; Charter & Tischner, 2017). Some of the key sustainability assessment strategies in product design are captured in the following subsections.

6.1 Environmental Impact Assessment Tools

Environmental impact assessment tools are widely used to evaluate the ecological implications of product design decisions and identify opportunities to reduce emissions, energy consumption and resource use (Hauschild et al., 2018). Life cycle assessment (LCA) is one of the most widely applied methods for evaluating environmental impacts across all stages of a product lifecycle, from raw material extraction to end-of-life disposal (ISO 14040; Hauschild et al., 2018). LCA helps identify major environmental burdens such as greenhouse gas emissions, energy consumption and resource depletion.

Additional tools complement LCA, including carbon footprint analysis, which measures greenhouse gas emissions and material flow analysis (MFA), which examines material movements within production systems to improve resource efficiency (Brunner & Rechberger, 2017). Eco-design tools also support the selection of environmentally preferable materials and the improvement of product recyclability (Luttropp & Lagerstedt, 2006).

6.2 Applications of Life Cycle Assessment

Life cycle assessment is widely applied in product development to compare alternative materials, manufacturing processes and product configurations (Hauschild et al., 2018; Tukker, 2015). By quantifying lifecycle impacts such as energy use, emissions, and material consumption, LCA supports evidence-based design decisions. LCA has been applied across several industries, including automotive manufacturing, consumer electronics and packaging design. For example, LCA studies have evaluated the environmental benefits of lightweight vehicle materials and alternative energy technologies (Bocken et al., 2016).

One important contribution of LCA is the identification of lifecycle hotspot stages that contribute the greatest environmental impacts. Identifying these hotspots enables designers to prioritize improvements that deliver the greatest sustainability benefits (Geissdoerfer et al., 2017). Despite challenges related to data availability and methodological complexity, LCA remains a key tool for sustainability evaluation in product design.

6.3 Circular Economy Strategies in Product Design

Circular economy principles aim to maintain the value of products and materials for as long as possible, in contrast to traditional linear production systems based on a “take–make–dispose” model (Geissdoerfer et al., 2017; Tukker, 2015). In product design, circular strategies emphasize durability, repairability, and recyclability. Design for durability extends product lifespan, while design for disassembly enables products to be easily repaired, remanufactured, or recycled (Bocken et al., 2016). Modular product architectures and accessible connectors are often used to support these approaches.

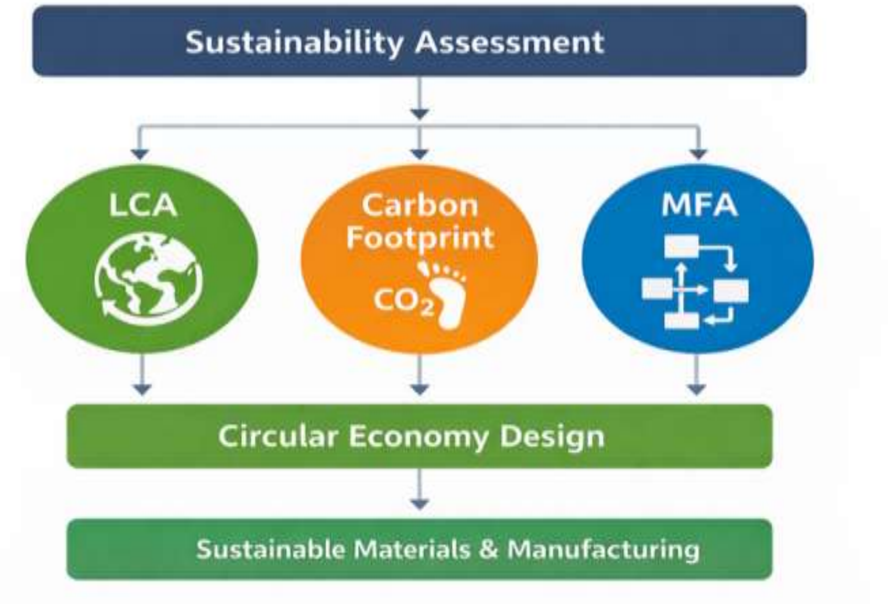
Another important model is the product–service system (PSS), where companies provide product functionality as a service rather than selling the product itself. This approach encourages manufacturers to design durable and maintainable products that maximize resource efficiency (Tukker, 2015).

6.4 Sustainable Materials and Manufacturing

The choice of materials and the production methods also play a key role in determining the environmental performance of a product. Sustainable development of the product, in its turn, focuses on the utilization of environmentally friendly materials and resource-efficient technologies of production (Allwood et al., 2012; Hauschild et al., 2018). Examples are recycled metals, recycled plastics and bio-based materials obtained on the basis of renewable resources, which can save energy and greenhouse gas emissions in comparison with conventional materials (Charter & Tischner, 2017).

The environmental performance is also improved through sustainable manufacturing practices like cleaner production technologies, energy-efficient production processes, and waste reduction plans (Allwood et al., 2012). New technologies, such as additive manufacturing and digital manufacturing systems, contribute to sustainability even more by making materials more efficient and allowing to monitor resource consumption better.

Figure 6. Sustainability assessment methods used in product design



7. INTEGRATING ERGONOMICS AND SUSTAINABILITY

Sustainability analysis and ergonomic design are also taking a major research interest in sustainable product development. Traditionally, ergonomics focused on the maximization of the human-systems interactions and the sustainability studies were conducted to examine the environmental and economic impacts of products during their lifecycles (Zink, 2014; Dul and Weerdmeester, 2008). Recent studies show that human factors are significant in sustainability outcomes, particularly when it comes to the product use phase (Thatcher and Yeow, 2016; Geissdoerfer et al., 2017).

The environmental performance is highly influenced by user behavior and product usability. The inefficient use of energy, higher maintenance, or early replacement of the product can be caused by its poor design (Sabbaghi and Behdad, 2017; Lockton et al., 2013). A combination of ergonomic design and sustainability assessment thus offers a useful solution to enhancing the environmental performance and user well-being (Hauschild et al., 2018; Bocken et al., 2016).

Figure 7. Integration of ergonomics and sustainability in product design

7.1 Human-Centered Sustainability Frameworks

Human-based sustainability models focus on the incorporation of human aspects into the processes of sustainability-based designs. They are based on human-centred design, emphasising the needs of the users, their usability, and their continuous assessment during the development of a product (Harte et al., 2017; ISO 9241-210).

Recent research suggests integrating the ergonomic assessment with the sustainability assessment instruments, including the life-cycle assessment, to make sure that the improvement of the environmental performance does not affect the usability or user acceptance (Hauschild et al., 2018; Bocken et al., 2016). These frameworks usually touch upon three aspects, namely user well-being, environmental performance and behavioral sustainability, promoting safe, efficient and environmentally responsible use of products (Geissdoerfer et al., 2017; Zink, 2014).

7.2 Synergies Between Ergonomics and Environmental Performance

The environmental performance can be improved through ergonomic design, which affects the interaction of the users with the products. Products that are easy to use and intuitive have higher chances of being efficiently utilized and have a longer service life, which is sustainable consumption (Sabbaghi and Behdad, 2017; Lockton et al., 2013).

Energy-efficient operation can be motivated by ergonomic interfaces with a clear feedback and intuitive controls, especially in appliances and electronic equipment (Lockton et al., 2013; Bocken et al., 2016). Better usability also leads to the increased product life, decreased early disposal, material usage and decreased waste (Geissdoerfer et al., 2017).

Ergonomics also contributes to sustainability in manufacturing systems by enhancing the efficiency of workers, decreasing fatigue and minimizing the number of errors in production, reducing the amount of material waste and consumption of resources (Zink, 2014; Allwood et al., 2012).

7.3 Trade-Offs and Emerging Integrated Design Models

In spite of these synergies, we may have trade-offs between usability and environmental performance. To give an example, sustainable materials like recycled or bio-based materials can impact the product lifespan or usability, whereas new energy-efficient technologies can create cognitive workload when the interface is not designed in an intuitive manner (Charter & Tischner, 2017; Hauschild et al., 2018; Wickens et al., 2015).

To overcome these issues, designers are more willing to use combined strategies and consider usability, environmental performance and economic aspects at once (Bocken et al., 2016). New models integrate the idea of ergonomics with the concept of lifecycle sustainability analysis at the initial design phases, allowing the simultaneous consideration of the human-product interaction and environmental consequences (Hauschild et al., 2018; Geissdoerfer et al., 2017).

Sustainable user experience (SUX) is also a recent research topic that applies UX design principles to promote sustainable consumption and product longevity (Hassenzahl, 2010; Lockton et al., 2013). In general, the incorporation of ergonomics and sustainability necessitates the interdisciplinary interaction between ergonomics, sustainability science and design engineering.

8. DISCUSSION

The results show that despite the popularity of the ergonomic design and sustainability assessment in the product development research, there is still a lack of integration between them. Most of the studies concentrate on usability enhancement based on ergonomic design or on environmental analysis based on sustainability assessment instruments, including life-cycle assessment (LCA). There is a lack of studies that specifically examine the contribution of ergonomic principles to the sustainability performance of product lifecycle (Zink, 2014; Hauschild et al., 2018; Bocken et al., 2016). The literature review reveals the significance of human-centred design in influencing sustainability results, especially in the stage of product use. The user behavior, interaction design and usability impact on the energy consumption, product life and maintenance practices (Thatcher et al., 2019; Lockton et al., 2013). The sustainable product development based on ergonomic considerations can thus enhance the environmental performance and user experience (Silander, 2019; Geissdoerfer et al., 2017).

8.1 Key Insights from the Review

The discussion indicates a number of important insights. First of all, human-centred design has a great influence on sustainable use of products. Ergonomics, including simple controls and user-friendly interfaces, can enhance efficiency in operations and minimize the error of users (Rossi & Attaianese, 2023; Hassenzahl, 2010). Second, product design is also becoming increasingly implemented using lifecycle thinking where ergonomics influences the sustainability outcomes of each stage of the process, including manufacturing, product use, maintenance and end-of-life processes (Luttropp & Lagerstedt, 2006; Hauschild et al., 2018). Third, user behavior is a very important aspect of sustainability performance. The ergonomic design can inform efficient product utilization by means of feedback and user-friendly interaction design (Lockton et al., 2013).

Lastly, the literature mentions the increased interdisciplinary cooperation of ergonomics, sustainability science and industrial design in order to handle the issue of sustainable product innovation (Bocken et al., 2016; Tukker, 2015).

8.2 Research Gaps

Although there is growing interest in research, there are still a number of gaps. One of the major limitations is the lack of integrated systems, which combine the ergonomic assessment and the sustainability assessment tools. Most sustainability strategies are highly sensitive to the indicators of the environment and rarely consider the usability or behavioral factors (Hauschild et al., 2018). The other gap is that there is a lack of empirical evidence that connects the ergonomic design features to the sustainability outcomes. Even though conceptual research indicates that better usability may promote sustainable behavior, not many studies quantitatively test the relationships (Silander, 2019; Geissdoerfer et al., 2017). Also, the new technological settings of smart products, digital manufacturing, and Industry 4.0 have not been explored in terms of integrating ergonomics and sustainability (Allwood et al., 2012) (Table 2).

8.3 Implications for Product Designers

The results have a number of implications to the product designers who come up with sustainable products. To start with, designers are advised to implement human-centred design methods, which allow engaging users in the design process and thus learn more about the interaction patterns and usability needs (Harte et al., 2017). Second, sustainability evaluation must be included at the initial stages of design that will allow designers to consider other product ideas in terms of usability and environmental performance (Hauschild et al., 2018).

Third, the lifecycle perspective enables designers to take into account the impact of design choices on manufacturing productivity, user behavior, maintenance needs, and end-of-life operations (Tukker, 2015). Last but not least, there should be a focus on increasing product life and user satisfaction since the longer the product life, the less resources are used and the less waste is produced (Bocken et al., 2016).

8.4 Implications for Engineering and Human Factors Research

Ergonomics and sustainability integration also has research opportunities in industrial engineering and human factors. Integrating the sustainability assessment tools with the ergonomic assessment methods, including the usability testing and the cognitive workload analysis, may allow conducting a more holistic evaluation of the product performance (Wilson, 2014; Dul and Weerdmeester, 2008).

The research in human factors can also help in this respect by investigating the effect of product design on the user behavior and pattern of consumption of resources. The knowledge of such relations can be used to design products and systems that promote efficient energy consumption and sustainable product operation (Lockton et al., 2013).

Table 2 – Research Gaps and Future Research Agenda

Research Area	Identified Research Gap	Future Research Directions	Key References
Integration of Ergonomics and Sustainability	Limited frameworks integrating ergonomic evaluation with sustainability assessment methods.	Develop integrated design frameworks combining human-centered design, ergonomic evaluation, and lifecycle sustainability assessment.	Zink (2014); Hauschild et al. (2018); Bocken et al. (2016)
User Behaviour and Sustainability	Insufficient empirical evidence linking ergonomic design to sustainable user behaviour and energy consumption patterns.	Conduct experimental and behavioural studies examining how product design influences energy usage and user interaction.	Harte (2017); Lockton et al. (2013)
Lifecycle-Oriented Ergonomic Design	Limited research examining ergonomic considerations across the entire product lifecycle.	Develop lifecycle-based ergonomic design models addressing manufacturing, usage, maintenance, and end-of-life stages.	Luttropp & Lagerstedt (2006); Geissdoerfer et al. (2017)
Digital Technologies and Sustainability	Limited studies exploring ergonomics–sustainability integration in smart products and Industry 4.0 environments.	Investigate the role of digital human modelling, simulation tools, and smart systems in sustainable product design.	Allwood et al. (2012); Wickens et al. (2015)
Social Sustainability and Human Well-Being	Sustainability research often prioritizes environmental indicators while neglecting human well-being and usability aspects.	Integrate ergonomic indicators such as usability, accessibility, safety, and well-being into sustainability assessment frameworks.	Dul & Weerdmeester (2008); Zink (2014)
Circular Economy Design	Limited research linking ergonomics with circular product design strategies.	Explore ergonomic design approaches that support repairability, modular design, and product longevity in circular-economy systems.	Bocken et al. (2016); Tukker (2015)

8.5 Future Research Directions

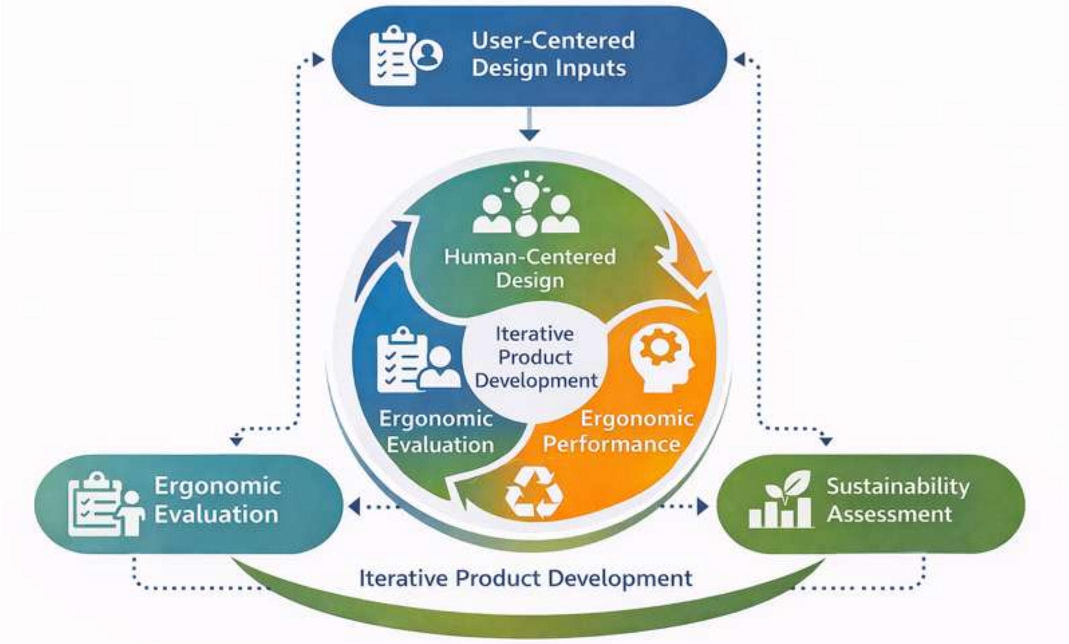
Future studies are needed to come up with integrated design frameworks, which integrate ergonomic assessment with sustainability assessment approaches to facilitate human-oriented sustainable product development (Hauschild et al., 2018). More empirical and industry-grounded research is required to learn more about the way ergonomic design can impact product lifecycle sustainability results (Bocken et al., 2016). Studies should also focus on how digital technologies, simulation tools and smart product systems can facilitate integrated ergonomic and sustainability analysis (Allwood et al., 2012).

Also, further research ought to broaden the sustainability research to encompass social sustainability and user well-being, so that sustainable products can contribute to the environmental responsibility and positive user experiences (Zink, 2014).

9. PROPOSED CONCEPTUAL FRAMEWORK

The results show that studies on ergonomics design and sustainability evaluation in product development are still divided. Usability and human performance are the most common subject of ergonomic research, whereas sustainability research typically analyses environmental effects through approaches like life cycle assessment (LCA) (Hauschild et al., 2018; Bocken et al., 2016). Consequently, the number of integrated frameworks that integrate human factors with sustainability assessment is minimal.

Figure 8 – Proposed Ergonomics – Sustainability conceptual framework



To fill this gap, this paper will suggest a conceptual framework of ergonomics-sustainability that incorporates the principles of human-centred design with sustainability assessment throughout the product development cycle. The framework intends to enhance usability, user experience and environmental performance at the same time. Past research indicates that user behavior and human-product interactions play a major role in determining the lifecycle sustainability results (Wilson, 2014; Lockton et al., 2013; Zink, 2014).

9.1 Integrated Ergonomics–Sustainability Model

The conceptualization of sustainable product development proposed is that it is an interaction between human factors, technological design, and environmental performance. In contrast to traditional sustainability models, which mostly concentrate on material and energy efficiency, this model acknowledges that user interaction and usability are also important factors to consider when it comes to lifecycle environmental performance (Wickens et al., 2015; Geissdoerfer et al., 2017).

The framework incorporates three major dimensions:

- Human-centered design, aims at learning the needs, capabilities and context of use of the user.
- Ergonomic performance, measures usability, safety and cognitive or physical comfort.
- Sustainability performance, evaluating the environmental effects of the product lifecycle.

These dimensions are interrelated in a cyclic design cycle that helps designers to improve product ideas with the help of usability testing and sustainability analysis feedback (Hauschild et al., 2018; Tukker, 2015).

9.2 Framework Components

The model consists of four interactive elements that facilitate integrated sustainable product development.

User-Centered Design Inputs

This aspect entails the identification of user requirements, behavior and contexts of use by using user interview, observational research and usability testing techniques. The need to consider the input of the user in the initial design phases enhances the usability of the product and encourages the practice of sustainable consumption (Rossi & Attaianese, 2023; Hassenzahl, 2010).

Ergonomic Evaluation

Human-product interactions are evaluated using the ergonomic evaluation techniques that include usability testing, anthropometric analysis, and cognitive workload analysis. Such techniques assist in determining the problem of usability and minimizing the number of user errors that can result in the ineffective use of a product (Dul and Weerdmeester, 2008; Wickens et al., 2015).

Sustainability Assessment
Sustainability assessment tools are used to evaluate the environmental performance and include life-cycle assessment, carbon footprint analysis, and material efficiency indicators. Such tools allow designers to recognize the hotspots in the lifecycle environmental impact and compare the alternative design solutions (Hauschild et al., 2018; Allwood et al., 2012).
Iterative Product Development
The last element is the iterative design process which incorporates both the ergonomic assessment and the sustainability assessment. The constant feedback of usability testing and environmental analysis enables the designers to balance the usability and environmental performance of the product in its development (Bocken et al., 2016).

9.3 Framework Application
The suggested framework will be able to facilitate sustainable product development in a variety of design phases. User research is useful during the initial design stages to determine the interaction requirements and usability constraints. This can be followed by applying ergonomic analysis and sustainability analysis at the same time to different design options in order to compare them according to their usability, environmental effects and resource efficiency.
Later during the development life cycle, prototype testing and life cycle assessment can be used to confirm the product meets the ergonomic and sustainability goals. The framework allows developing products that contribute to the well-being of the users and reduce the environmental effects (Geissdoerfer et al., 2017; Tukker, 2015).

10. PRACTICAL IMPLICATIONS
The combination of ergonomic design and the sustainability evaluation have significant implications on the industry, product designers, and policymakers. Although the concept of sustainability has long been associated with minimizing the negative environmental effects by ensuring energy efficiency and optimizing the use of materials, the review demonstrates that the interaction between humans and products is crucial in determining sustainability (Bocken et al., 2016; Hauschild et al., 2018). Ergonomically designed products tend to be simpler to use, service, and fix, which may increase the lifespan of the products and promote responsible consumption behavior (Zink, 2014; Snyder, 2019).

10.1 Implications for Industry
When applied to the industrial organizations, sustainability assessment along with ergonomics can be used to improve the competitiveness of the products and the environment. Design lifecycle-based approaches enable organizations to assess the impact on the environment at various points, including sourcing of materials, production, use of the product and end-of-life (Hauschild et al., 2018). Inter-disciplinary cooperation involving engineers, designers and human factors specialists can also assist organizations to develop products that look at the objectives of usability and sustainability simultaneously (Tukker, 2015). In addition to that, circular economy concepts such as developing products in such a manner that makes them durable, repairable and modular can result in the production of waste being lower and an increase in resource use (Geissdoerfer et al., 2017).

10.2 Implications for Product Designers
In product designer case, there is need to have a holistic perspective of design where human factors, environmental impacts and lifecycle performance are all put into consideration. The user-centred design techniques, including usability testing and participatory design, can be used to offer useful information about user behavior and interaction patterns (Norman, 2013). Sustainability assessment tools, including life-cycle analysis, should also be used by designers at the initial design stages to compare the alternative concepts regarding environmental performance (Hauschild et al., 2018). Moreover, the design features that promote sustainable user behaviour, like intuitive interfaces and feedback mechanisms, may affect the energy usage and product usage behavior (Lockton et al., 2013).

10.3 Implications for Policy and Standards
Another implication of the combination of ergonomics and sustainability is on the policymakers who are mandated to formulate sustainability standards and regulations. The current policies tend to give more emphasis to the environmental indicators like energy efficiency and reduction of emissions and less on human factors.
Human-centred design considerations can be added to the sustainability standards to enhance the effectiveness of environmental policies. The international systems of lifecycle assessment and environmental management already offer systematic methods of assessing the sustainability of products (Hauschild et al., 2018). Ergonomic factors that enable repairability, maintenance and product longevity can also be applied to policy measures that encourage circular economy approaches, including extended producer responsibility and product durability rules (Geissdoerfer et al., 2017).

10.4 Limitations of the Study
There are a number of limitations that should be considered when interpreting the findings of this review. To begin with, the literature search has been based on the large academic databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Even though these databases are very comprehensive in terms of peer-reviewed publications coverage, specialized databases or industry sources might have not been covered with the relevant studies.
Second, the review concentrated on the publications between 2000 and 2025, which might have omitted the older studies related to ergonomics and sustainability integration. Third, the review can be affected by publication bias since the studies with significant results are more likely to be published than the ones with inconclusive results (Dwan et al., 2013).
Lastly, the research topic is interdisciplinary, which also creates methodological issues. Ergonomics and sustainability

research cuts across various fields, such as industrial engineering, design research, and environmental science, which can employ various terms and methods of analysis. Nevertheless, the review offers a detailed synthesis of the existing research and outlines the most relevant possibilities to develop integrated ergonomic and sustainability design strategies.

11. CONCLUSION

This paper was a systematic review to investigate the combination of ergonomic design and sustainability evaluation in product development. The results reveal that despite the popularity of ergonomics and sustainability, their combination in the research on products design is not well-established. Ergonomic studies are mostly concerned with usability and human performance and sustainability studies are mostly concerned with environmental impact assessment using tools like life-cycle assessment. The review points out that ergonomic design plays a significant role in determining the results of sustainability in terms of user behavior, product usability and product lifespan. In order to fill the identified gap, this paper suggests a combined conceptual framework of human-centred design, ergonomic analysis and sustainability analysis. A combination of these views can be used to design products that will enhance the well-being of users and minimize environmental effects.

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