Revolutionizing Age Determination: Theoretical Insights into Radiocarbon (^{14}C) Dating[1]

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Abstract

Radiocarbon dating is a scientific method for determining the age of ancient organic materials, specimens, and artifacts based on the decay of ^{14}C isotopes. This study outlines the mode of formation and assimilation of ^{14}C isotopes in the atmosphere. A traditional carbon-14 dating method estimates sample age by measuring β-ray decay, however, this new technique uses an incredibly sensitive mass spectrometer to count individual carbon-14 atoms in a sample directly. This approach offers several advantages. It eliminates issues related to the cosmic ray background and allows for shorter counting times on much smaller samples, leading to more precise age determinations. Moreover, a wide range of archaeological materials can be dated using milligram-sized samples. Currently, research is underway to develop a specialized machine for counting C-14 atoms, and radiocarbon dating cannot provide exact dates for archaeological or environmental studies on its own. Instead, it needs to use a calibration curve to adjust for changes in atmospheric carbon levels. Any model that proposes the validity of C-14 dating must acknowledge its objectivity and reproducibility. The fundamental principles, methods, and methodology of accelerator mass spectrometry (AMS), and the history, evolution, and revolution in radiocarbon dating techniques are presented in this review.

Keywords: Accelerator-mass spectrometer, Age determination, Isotopic analysis

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Introduction

Radiocarbon dating is a widely used scientific method for determining the age of ancient organic materials and significantly affects fields such as archaeology and geology (Becerra- Valdivia & Higham, 2023). This method, developed in the 20th century, was originally inspired by the study of cosmic rays and their effects on Earth's atmosphere (Strohmaier, 2023). Early explorations by Rutherford and Frederick Soddy in 1902 laid the groundwork for this technique by investigating the potential of radioactive carbon to date rocks and minerals. Willard Libby, a chemist at the University of Chicago, proposed this concept in the 1940s, which led to the modern practice of radiocarbon dating (Hajdas et al. 2021a). Radiocarbon dating relies on the predictable decay of carbon-14 (^{14}C) which follows the first-order kinetics. Radiocarbon (^{14}C) absorbed during an organism's lifetime begins to diminish in organic matter once an organism dies. By measuring the remaining amount of ^{14}C in a sample and comparing it to atmospheric levels at that time, the approximate age of the material can be calculated. The fluctuation in atmospheric ^{14}C levels over time resulting from natural processes, such as solar activity and volcanic eruptions, and human activities, such as the burning of fossil fuels necessitate careful calibration (Wertnik et al., 2023). Calibration curves designed from data sources such as tree rings and coral allow for more accurate dating by compensating for these variations. Such advancements have broadened the scope of radiocarbon dating, enabling its use in more refined and complex chronological reconstruction across multiple disciplines (Pearson et al., 2022).

Despite its success, radiocarbon dating is not free from limitations, as the method becomes less reliable for dating materials older than 50,000 years. This is because of the negligible activity of ^{14}C after that period. Furthermore, contamination from recent carbon sources or the presence of materials that are not truly organic can skew results. The old carbon that has resides in fossil fuels or other reservoirs for millennia can lead to the formation of artificially old carbon. Therefore, the accuracy and reliability of radiocarbon dates depend on careful sample preparation and purification techniques. Advances in these techniques have helped mitigate these issues, particularly in environmental and archaeological contexts (Hajdas et al., 2021a).

The most well-known application of radiocarbon dating is in archaeology, which has transformed the study of ancient human settlements, such as those of the Maya and the Incas (Ziółkowski et al., 2022). It enables researchers to date organic materials up to approximately 50,000 years of age, providing insight into human history across Europe, America, and Asia (Taylor, 2020a). In recent years, it has also gained momentum in the study of climate change, tree growth, and the remains of humans and animals (Crema & Bevan, 2021). Libby hypothesized that carbon-14 (^{14}C), a naturally occurring isotope formed by cosmic rays in the upper atmosphere, could be used to date organic materials. The success of this technique revolutionized archaeology and other scientific fields, and radiocarbon dating has become widely accepted as a reliable method for dating bones, charcoal, and organic sediments (Solís et al., 2024).

In addition to archaeology, radiocarbon dating has also been applied in environmental studies. It is used to date plant remains, soil, and water, providing insights into past climatic conditions, vegetation, and geological events (Quarta et al., 2021) When combined with methods such as dendrochronology and varve chronology, radiocarbon dating provides a more comprehensive understanding of the environmental history across different regions. Accelerator mass spectrometry (AMS) has further revolutionized radiocarbon dating, offering increased precision and the ability to analyze much smaller samples (García-León, 2022). However, challenges arise from the Suess effect, a phenomenon where fossil fuel emissions from the Industrial Revolution reduced the ratio of ^{14}C to ^{12}C in the atmosphere, making postindustrial radiocarbon dating more complex (Michaud et al., 2024)

Formation of carbon-14 and its incorporation into living organisms

Carbon-14 is the most significant isotope used in research, which helps clarify past events by establishing a chronological order. As a result, the study of its origin, disintegration process, half-life, and incorporation into living organisms is becoming increasingly significant. Since its formation, the Earth has been constantly bombarded by cosmic rays, which originate from outer space, and are composed mainly of protons (approximately 90%), atomic nuclei, and electrons. Carbon-14 isotopes are naturally produced in the atmosphere when cosmic rays collide with nitrogen atoms, converting them to carbon-14. This isotope undergoes oxidation to form carbon dioxide, which is then absorbed by plants during photosynthesis (Agrawal & Malviya, 2023). When animals consume these plants, carbon-14 becomes an integral component of their organic matter. Figure 1 shows the mechanism of assimilation and disintegration of C-14 isotopes in the environment.

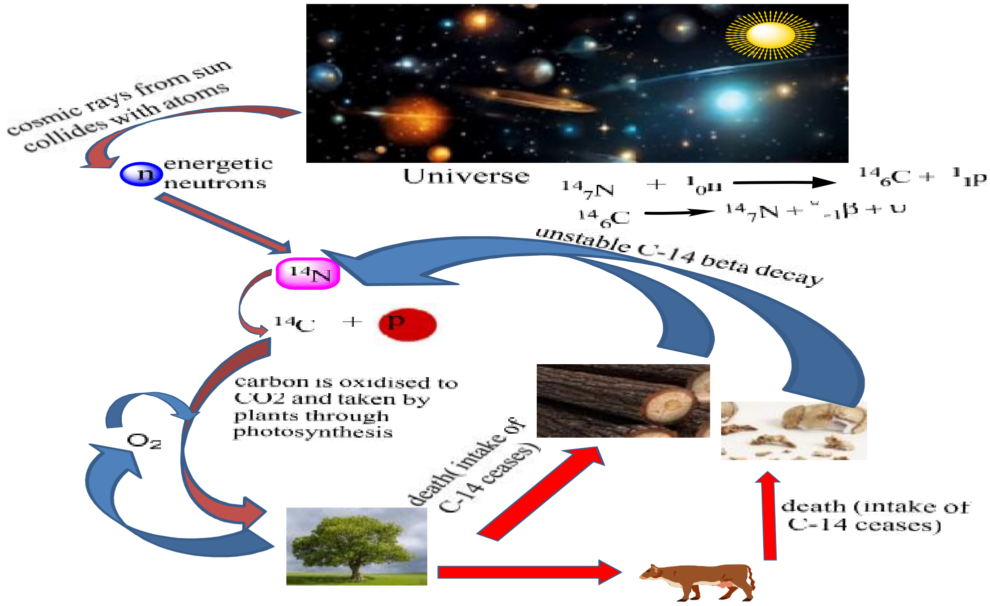

Figure 1: *Path of assimilation and disintegration of C-14 isotope in the atmosphere*

Principles of radiocarbon dating

Radiocarbon dating is based on the principle of radioactive decay, specifically, the decay of C-14 isotopes in organic materials. Living organisms absorb carbon from the atmosphere including trace amounts of radioactive C-14. Upon death, this absorption ceases, and C-14 within the organism decays at a known rate into nitrogen-14 with a half-life of approximately 5,730 years (Chen, 2023). This predictable decay rate serves as the foundation for radiocarbon dating, allowing scientists to calculate the age of organic samples using established mathematical formulas. Instead of relying on individual radiocarbon dates, recent approaches have aggregated multiple dates into chronological models to test specific hypotheses. This shift enhances the accuracy and precision of radiocarbon dating, broadening its application and improving cost-effectiveness by reducing the required sample size (Wood, 2015).

Radiocarbon dating experiments are conducted under controlled laboratory conditions using either traditional beta emission counting methods or advanced techniques such as Accelerator Mass Spectrometry (AMS). These methods align with a strict scientific approach based on quantitative data and statistical analysis to address uncertainties (Hajdas et al. 2024). Factors such as solar activity and variations in cosmic ray intensity can cause fluctuations in C-14 production, affecting the accuracy of dating results (Heaton et al., 2024). Calibration is essential to mitigate these effects, and calibration curves have been developed through extensive research and have been adjusted for these fluctuations. Cross-verification with other dating methods, such as dendrochronology and stratigraphy, further validates radiocarbon dates (Talamo et al., 2023).

Conventional radiometric techniques, such as beta-decay counting measure C-14 concentrations. Beta particles from C-14 decay can be detected using gas proportional counters (GPC) or liquid scintillation counters (LSC). GPCs utilize gases such as CO_2 or methane, where beta particles ionize the gas, whereas LSCs require the conversion of samples to benzene, mixed with scintillant chemicals. These techniques allow for precise measurement of beta particles emitted from C-14 decay (Banerji et al., 2022).

Technological advancement in radiocarbon dating

Radiocarbon dating using an accelerator mass spectrometer (AMS) has revolutionized our ability to measure ^{14}C concentrations accurately. Although AMS did not increase the theoretical age limit of radiocarbon dating, it significantly reduced the required sample size (from g to mg) and the measurement time from days to minutes, depending on both the sample size and desired level of analytical precision (Becerra- Valdivia & Higham, 2023). AMS measures trace amount of carbon-14 in a sample and compares them to other carbon isotopes, enabling highly sensitive analysis. Despite initial advancements certain environmental factors such as the Suess effect caused by burning fossil fuels, the barrier that exists between the atmosphere and ocean in carbon dioxide exchange, and insights from radiocarbon fallout, have complicated the accuracy of radiocarbon dating (Povinec et al., 2024). Over time, refinements have been made to improve the precision. Some of the key advancements include:

1. **Accelerator mass spectrometry (AMS):** The development of AMS marked a significant advancement in radiocarbon dating, allowing for the analysis of small samples within hours, unlike traditional methods that require large samples and take weeks.It is more sensitive, allowing the detection of minute quantities of ^{14}C (Fichter et al., 2024).
2. **Improved calibration curves:** Calibration curves used to convert measured ^{14}C levels in the calendar ages were significantly refined. IntCal20, released in 2020, incorporates over 15,000 radiocarbon measurements, globally. This curve corrects

for fluctuations in atmospheric ^{14}C levels, enhancing dating accuracy (McDonald & Manning, 2023)

3. **Bayesian statistics:** The application of Bayesian statistics to radiocarbon dating combines prior knowledge with new radiocarbon data to improve age estimates. This statistical method helps to incorporate uncertainties and multiple data sources, such as archaeological evidence, to achieve more precise outcomes (Price et al., 2021)
4. **Compound-specific radiocarbon analysis (CSRA):** Radiocarbon dating traditionally uses bulk organic materials, but new techniques now measure ^{14}C levels in specific molecules within a sample. The CSRA method offers more precise age estimates and can help trace the origins of different organic materials (Yamamoto et al., 2024).
5. **High-resolution dating:** High-resolution radiocarbon dating uses small, sequential samples to measure ^{14}C levels over time, providing a detailed chronology for studying events such as climate change and Cultural Revolution. However, it requires highly sensitive instruments such as AMS and can be labor-intensive and costly.

Radiocarbon dating process and calibration

The first step in radiocarbon dating is to obtain a sample of organic materials such as wood, charcoal, bone, or cloth. It is crucial to remove impurities in order to ensure accurate results. The physical examination of the samples was performed microscopically. The second step involves chemical cleaning using various organic solvents to dissolve any attached fats, ensuring that isolated carbon comes only from the sample (Szidat et al., 2017). Subsequently, the sample converts into CO_2 gas. This was done by loading the sample into a combustion tube with copper oxide and silver wire and then placing the tube under a vacuum to remove all air. The tube was sealed and heated in a muffle furnace at approximately 900 °C. Copper oxide facilitated the combustion of the sample, producing CO_2 and water. Once the tube was cracked open, CO_2 was transferred to a small bottle. The final step is the transformation of CO_2 into graphite. CO_2 was combined with H_2 gas in a graphite-reacting vessel using iron powder as the catalyst. When the mixture was heated to high temperatures, CO_2 was reduced to elemental carbon in the form of graphite. The graphite sample was then transferred to an AMS for the measurement. AMS ionizes the carbon atoms in the sample and accelerates them to high speeds using an electric field (Kieser, 2023). Carbon atoms were sorted and detected based on their mass-to-charge ratio, which is essential for accurate radiocarbon dating. A flow sheet diagram of the radiocarbon dating process is shown in Figure 2.

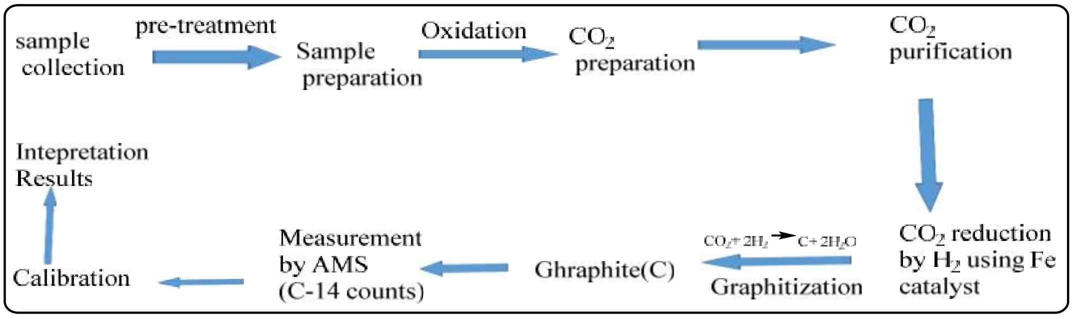

Figure 2: *Flow sheet diagram for the Carbon dating process*

After determining the C-14 content, the age of the sample was calculated using a mathematical formula based on the known decay rate. The age is reported in years "before present" (BP), with 1950 as the reference year. This was accomplished by comparing the amount of carbon-14 in the sample to the known amount in the atmosphere at the time of the sample's existence. The results were calibrated to account for fluctuations in atmospheric carbon-14 levels over time (Heaton et al., 2024). If the carbon-14 concentration in the atmosphere remained constant, calibration would not be needed. However, variations occur, leading to the use of several calibration methods, each with its own assumptions and conventions. Common calibration curves include the following:

1. **Libby's half-life**: Radiocarbon dating was developed in the 1940s by Willard Libby, who proposed this calendar. Using the half-life of C-14, the age of a sample can be calculated under the assumption that the decay rate remains constant over time. Libby radiocarbon age (T) was determined using the following equation:

$$T = 8033 \ln (A/A_0)$$

A = ^{14}C activity at the time of dating

A_0 = initial ^{14}C activity at time t_0 (death)

$T_{1/2}/\ln 2$ = 8033 yr, where $T_{1/2}$ = 5568 yr(half-life used by Libby)

However, Libby's half-life was accepted for conventional radiocarbon ages that can be modified to a half-life of 5730 years in radiocarbon ages (Becerra- Valdivia & Higham, 2023) ($t_{5730} = 1.03\ t_{Libby}$).

2. **IntCal:** The IntCal calibration curve is a widely used tool for calibrating radiocarbon data. It is constructed from measurements obtained from tree rings, marine sediments, and various other materials. This curve is periodically updated with new data, enhancing the accuracy of radiocarbon dating (Manning et al., 2024)
3. **SHCal:** The Southern Hemisphere Calibration Curve was specifically designed for calibrating radiocarbon dates in the Southern Hemisphere, where calibration materials are less abundant than in the Northern Hemisphere. This curve is derived from measurements of tree rings in the Southern Hemisphere, enabling a more accurate calibration of radiocarbon dates for that region (Bronk Ramsey et al., 2023)
4. **Marine04**: The Marine04 calibration curve is used for dating marine samples, which presents greater challenges than dating terrestrial samples because of the variability in carbon-14 content in the oceans over time. This curve is constructed from measurements of corals, foraminifera, and other marine materials and is periodically updated as new data emerge (Heaton et al., 2023).
5. **CALIBomb**: The CALIBomb calibration curve was used to adjust the radiocarbon dates from the period following the nuclear bomb detonations in the 1950s and the 1960s, which significantly elevated C-14 levels in the atmosphere. This calibration method relies on tree-ring measurements to correct for the "bomb effect" in radiocarbon dating (Pigorsch et al., 2022)

Radiocarbon dating: Accuracy and calibration

The activity of ^{14}C remaining in a sample is critical for determining its age through radiocarbon dating. Since C-14 decays at a known rate, with a half-life of approximately 5730 years, a sample containing half of its original C-14 would be estimated to be approximately 5730 years old. Similarly, a sample with one-quarter of its original C-14 content was approximately 11,460 years old (Figure 3). For samples older than 50,000 years, the amount of C-14 was theoretically undetectable owing to extensive decay. Therefore, the detection of C-14 in a sample provides reliable evidence that the sample is not millions of years old.

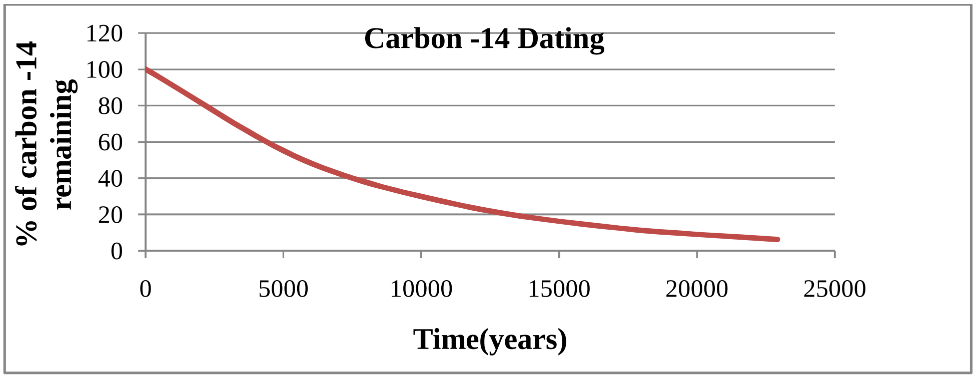

Figure 3: *A plot showing carbon -14 remaining vs. half-life*

Radiocarbon results are typically presented as BP (Before Present), representing the estimated age of an object, assuming a constant level of C-14 in the atmosphere. However, this assumption is rarely accurate because of frequent anomalies such as the Suess and Bomb effects. To account for these fluctuations, results were normalized and calibrated to calendar dates (cal AD).

Limitations and challenges of radiocarbon dating

Despite being powerful tools for archaeologists and scientists, radiocarbon dating has several inherent limitations and challenges. One key assumption in carbon-14 dating is that the activity of carbon-14 in ancient samples should match that of the modern reference samples used in laboratories. However, this assumption may not always be accurate. Libby assumed that cosmic-ray intensity and the size of the carbon exchange reservoir remained constant over time. Evidence shows that this assumption holds only for the past 4,000 years. I addition, several important limitations of this study should be considered:

1. **Limited age range:** Radiocarbon dating is effective only for carbon-containing materials up to approximately 55,000 years old. Consequently, they cannot be used to date materials that are millions of years old, such as rocks and most fossils, which require other dating methods.
2. **Contamination:** Radiocarbon dating requires that the sample is entirely free from contaminating carbon, which can be challenging to accomplish in practice. Minimal contamination can significantly distort the results.
3. **Calibration:** Radiocarbon dating operates on the assumption that the ratio of C-14 to C-12 in the atmosphere remains constant over time. However, this ratio has fluctuated due to natural factors such as solar activity, geomagnetic changes, and

variations in the global carbon cycle, as well as anthropogenic influences such as nuclear bomb testing and the burning of fossil fuels. Therefore, radiocarbon dates must be calibrated using other methods to account for these variations. If C-14 concentrations in the atmosphere remained constant throughout history, calibration would not be necessary.

4. **Sample size:** Radiocarbon dating typically requires a relatively large sample size, typically a few grams of carbon. This can pose challenges when working with rare or difficult-to-obtain materials such as archaeological artifacts.
5. **Precision:** Radiocarbon dating yields a range of possible ages rather than a precise date. This variability arises from factors such as fluctuations in the C-14/C-12 ratio in the atmosphere and variations in the rate of radioactive decay. Consequently, these factors can influence the amount of C-14 present in a sample, leading to uncertainties in the estimated ages.

Applications in science and history

Radiocarbon analysis has been a valuable tool for studying human and Earth history over the past 55,000 years (Hajdas et al., 2021b). The application of radiocarbon dating is continuously expanding because of new interdisciplinary research. Here we address the applications of radiocarbon dating in archaeology, environmental and climatic studies, and historical verification. These fields are among the most frequent users of this technique and have significantly contributed to its development compared with other areas of study. Radiocarbon dating has revolutionized carbon dating in the archaeology of ancient artifacts made from materials such as wood, bone, charcoal, textiles, and even seeds or grains (Palincaş, 2017). In the estimation of the remaining C-14 in a sample, archaeologists can determine the time elapsed since the death of the organism; thus, dating is crucial for establishing the timelines of ancient civilizations (Taylor & Bar-Yosef, 2016). The dating of wooden structures in Neolithic settlements and Bronze Age artifacts is a great example that has helped researchers to better understand the advancement of human societies. The accuracy and precision of carbon dating allowed the refinement of archaeological chronologies by replacing older and less accurate methods, which were highly dependent on artifact styles (Sutton, 2022). Recent advancements in radiocarbon dating have helped clarify major historical periods. By dating ancient grains and tools, researchers have gained insight into the spread of the agricultural revolution. This evidence has shown that different regions have transitioned from hunter-age societies to farming communities. Carbon dating is used not only to date artifacts but also to analyze organic residues, such as plant debris or animal fats, found in pottery or human-used tools. This allows for a better understanding of the daily routines, diets, and rituals of prehistoric people (Bowman, 1990).

Radiocarbon dating is used in environmental and climate studies to reconstruct past environmental and climatic conditions, such as dating ice cores, which provide information about the Earth's atmosphere hundreds of thousands of years ago. Trapped gases and organic particles within the ice were used for dating. From these sources, researchers can determine greenhouse gas concentrations, such as CO_2 levels, and compare them with historical temperature records to understand how climate change has affected the planet over geological timescales. Additionally, soil carbon dating enables carbon cycle tracing, which is important for understanding how carbon moves in response to natural and human activity across the Earth's atmosphere, oceans, and land (MacFarling Meure et al., 2006).

Radiocarbon dating is useful when the historical documentation or supporting evidence is insufficient. It can date ancient structures, monuments, and manuscripts to confirm historical events and validate the timelines. It provides a more accurate reconstruction of history, eliminating the gaps between narratives and physical evidence. The reliability of radiocarbon dating has improved through cross-verification with methods such as dendrochronology and stratigraphy. This collaborative approach improves the precision of historical and archaeological dating (Stuiver & Becker, 1993). Table showcases some key examples of samples dated using this method, illustrating the far-reaching applications of this technique.

Table 1:
Radiocarbon dating data of notable artifacts, geological samples, methods used and significance

Sample/Artifact	**Location**	**Method Used**	**Age (yr BP)**	**Significance**	**% Dating Probability**	**Ref.**
Shroud of Turin	Italy	AMS	Medieval	Religious and historical artifact	95%	(Damon et al., 1989)
Dead Sea Scrolls	Qumran, Israel	AMS	~2,000 years	Ancient texts of religious and cultural importance	68%	(Bonani et al., 1992)
Ötzi the Iceman	Alpine Glacier (border of Austria/Italy)	AMS	~4600 years	Preserved human body; insights into prehistoric life	68.2%	(Vidale et al., 2018)
Kennewick Man	Washington,	LSC	~9,000	Ancient human	95%	(Taylor et

	USA		years	remains in North America		al., 1998)
Viking Settlement at L'Anse aux Meadows	Newfoundland, Canada	AMS	~1000 years	Confirms Viking presence in North America pre-Columbus	95%	(Nydal, 1989)
Machu Picchu	Peru	AMS	~500 years	Timeline for Inca civilization's expansion	68%	(Berger et al., 1988)
Wooden Artifacts from the Jomon Period	Japan	AMS	~7,000 years	Dates Neolithic culture; early pottery		(Morlan, 1967)
Sediments from Lake Suigetsu	Japan	AMS and GPC	Up to 52,800 years	Calibration reference; atmospheric carbon variations	95%	(Kitagawa et al., 1995)
Sutter's Mill Meteorite Organic Compounds	California, USA	CSRA	~4,600 million years	Ancient organic molecules from meteorites	68%	(Jilly et al., 2014)
Skeletal Remains from Sidrón Cave	Spain	AMS	~49,000 years	Insight into Neanderthal genetics and behavior	68%	(Torres et al., 2009)
Clovis Projectile Points	Various North American sites	GPC	~13,000 years	Evidence of early human presence in North America	95%	(Jr., 1987)

AMS: Accelerator Mass Spectrometry, **LSC:** Liquid Scintillation Counting, **GPC:** Gas Proportional Counting, **CSRA:** Compound-Specific Radiocarbon Analysis

Revolutionary insights and prospects

Advancements in technology have significantly improved radiocarbon dating, allowing the use of smaller samples and providing more precise results, which expands its applications across various sectors (Taylor, 2020b). Various revolutionary insights and prospects have evolved as researchers continue to push the boundaries of carbon dating. However, these advancements in radiocarbon dating have raised ethical and environmental concerns that must be addressed. With the recent development in radiocarbon dating methods, AMS has become a convenient method to analyze even extremely small samples, in addition to its minimal destruction of artifacts. It is such a tool that provides results with greater accuracy and precision by directly detecting C-14 of a few milligrams in size (Bronk Ramsey, 2008). This tupe of enhancement is required, especially in fields such as archaeology and environmental science, where minimizing damage to precious or scarce samples is of utmost importance. The previously unresolved artifacts and timelines have now been easily resolved owing to the increased accuracy and precision of the different tools. In addition to the advancements in radiocarbon dating, which has helped humans understand their past, it has also raised ethical concerns regarding the destruction of ancient artifacts. The content of C-14 is measured by the combustion of the sample in radiocarbon dating; considering culturally valuable artifacts and their use in dating purposes may lead to controversy. Therefore, there is always a fragile balance between the utilization of artifacts to gain scientific knowledge on radiocarbon dating and the preservation of cultural heritage (Hajdas et al., 2019; Margariti et al., 2023). Concerning such issues, AMS has become the preferred method for dating valuable artifacts because it requires small sample preparation. This has reduced the destruction of artifacts, allowing researchers to date such items and to preserve much of their integrity.

In addition to ethical considerations, there are environmental concerns related to the collection and processing of samples for radiocarbon dating. The collection of samples from delicate ecosystems such as peat bogs and lake beds can cause disturbances and potentially disrupt the environment. Moreover, sample processing, such as the use of chemical agents to prepare samples and solvents to remove impurities from organic samples before dating, can lead to environmental pollution. These chemicals must be disposed of properly to prevent contamination of soil and water (Wood, 2015). In the future, it is essential to minimize the destruction of artifacts and enhance the sustainability of the samplse and their processing in radiocarbon dating. The far-reaching development of highly sophisticated techniques such as single ion AMS promises the dating of any kind of sample, even smaller samples, with high precision and accuracy, which would benefit the delicate or significant tests that were impossible previously (Matteson, 2008). The combination of radiocarbon dating with other methods such as optically stimulated luminescence (OSL) or uranium-thorium dating has the potential to cross-check and improve the accuracy of previously dated samples (Molodkov, 2012). The interdisciplinary approach of radiocarbons across different methods will help refine timelines and enhance the understanding of environmental and cultural processes.

Conclusion

Radiocarbon dating, based on the principles of radioactive decay and equilibrium within the biosphere, has been a transformative tool since its development in the 1940s. Recent advancements in techniques such as Accelerator Mass Spectrometry, enhanced calibration curves, Bayesian statistics, compound-specific radiocarbon dating, and high-resolution dating have significantly improved the accuracy and precision of this method, although results may still be affected by sample contaminations. These innovations have broadened its applications, allowing researchers to date a wide range of materials, from prehistoric artifacts and ancient human remains to geological samples. Although radiocarbon dating is highly effective for dating organic materials, it is crucial to recognize its limitations. Calibration techniques and cross-validation with other dating methods reduce the inherent uncertainties in the estimates provided by the method. When used in conjunction with complementary dating approaches, radiocarbon dating becomes a powerful tool in reconstructing past events and timelines, contributing to fields such as archaeology, geology, and paleoclimatology.

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