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# Evolution and Future of DNA Extraction Procedure

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***Abstract*—***DNA extraction holds paramount importance in forensic science, genetic research, and clinical diagnostics. It makes the DNA used for analysis in different applications including criminal investigations. After the mid-20$^{th}$ century, DNA extraction techniques evolved with early methods such as phenol-chloroform extraction which were labor-intensive and used hazardous chemicals. Over time newer techniques like silica-based, magnetic bead-based, and automated systems emerged making DNA extraction more efficient and accessible. Recent innovations include microfluidic and nanotechnology-based methods which aim to enhance yield and sensitivity, particularly for challenging samples like touch DNA. Still, limitations persist especially in handling low-template or degraded DNA samples. Current methods may lack the sensitivity or purity required for reliable analysis of trace DNA posing challenges in extracting usable DNA from minimal or compromised samples. Future innovations may yield breakthroughs that enable reliable DNA extraction even from a minute quantity of samples.*

***Keywords*—** *Automated systems, chelex extraction, DNA extraction, magnetic-beads, microfluidic, nanotechnology, Phenol-Chloroform, Salting-Out, silica-column, touch DNA.*

## I. Introduction

DNA extraction has served as the foundational step in molecular biology for over half a century facilitating a range of scientific fields including genetics, clinical diagnostics, and forensic science. The fundamental goal of DNA extraction is to isolate pure DNA from cellular material in a manner that preserves the quality and quantity of the extracted nucleic acid. The method chosen often depends on the nature and quantity of the sample as well as the intended downstream application which may require high sensitivity, minimal contamination, or the preservation of DNA integrity. [1][2]

Early methods like the phenol-chloroform extraction developed in the 1950s were based on organic solvents that separate nucleic acids from proteins. While effective these techniques involved hazardous chemicals and multiple steps that posed challenges for scalability and routine use. Over time techniques evolved with the development of salting-out methods in the 1980s which provided a safer and faster alternative but were less effective for certain types of samples [2].

In the 1990s silica-based and magnetic bead-based methods revolutionized the extraction landscape by providing more user-friendly high-throughput alternatives that increased purity and yield. These methods were particularly useful for forensic applications as they allowed the extraction of DNA from degraded or trace biological samples [3]. By the 2000s automated extraction systems became widely available enabling consistent and high-throughput DNA isolation with minimal human intervention ideal for both clinical and forensic settings [4].

Recent advancements in the 2010s and 2020s have focused on microfluidics and nanotechnology to improve extraction efficiency and sensitivity further. These methods hold promise for ultra-low quantity samples such as touch DNA—DNA left by incidental contact which typically exists in trace amounts and is prone to environmental degradation [5].

In forensic science, DNA extraction plays a critical role in identifying suspects, linking individuals to crime scenes, and exonerating the innocent. Touch DNA, however, presents unique challenges due to the small amounts of DNA present and the risk of contamination. Effective extraction techniques for touch DNA are essential for obtaining reliable forensic results yet current methods still face limitations in yield and sensitivity.

## II. DNA Extraction

DNA extraction is the process of isolating DNA from cells or tissues. It's a critical first step in various biological and forensic applications as it allows scientists to study genetic material in a purified form. The extraction process involves breaking down the cell membrane, separating DNA from other cellular components, and purifying it for analysis. Once extracted, DNA can be used for tasks like genetic testing, forensic identification, research on genetic diseases, and analyzing biological relationships. [6]

Typical DNA extraction involves (a) cell lysis, which is breaking open cells to release their DNA. This can be done chemically using detergents or enzymes or physically by grinding or blending. (b) Removal of Proteins and Other Contaminants: Proteinase K or other enzymes help digest proteins while additional reagents like salt solutions help



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separate DNA from other cell components. (c) DNA Precipitation: Alcohols like ethanol or isopropanol are added to precipitate DNA allowing it to be separated from the rest of the solution. (d) DNA Purification: The DNA is then washed and re-suspended in a buffer or water making it ready for downstream applications like PCR or sequencing [2].

DNA extraction is foundational in forensic science because it allows for the analysis of DNA samples left at crime scenes [7]. Improved DNA extraction techniques have made it possible to analyze very small samples such as those containing only a few skin cells making it increasingly valuable in solving cases with minimal biological evidence. DNA is of paramount importance such as in medical diagnostics where DNA extraction enables the diagnosis of genetic disorders and diseases including hereditary conditions and infectious diseases; in genetic research where extracted DNA is used to study genes, understand genetic relationships, and analyze evolutionary biology and in biotechnology where DNA is extracted for genetic engineering, cloning, and the production of genetically modified organisms (GMOs).

## III. Methods for DNA Extraction

### A. Phenol-Chloroform Extraction (1956)

The phenol-chloroform extraction method developed in the 1950s was one of the earliest and most foundational DNA extraction techniques in molecular biology. This method uses phenol and chloroform as organic solvents to separate DNA from proteins and cellular debris [8]. In a process known as cell lysis, the sample is combined with phenol and chloroform, vigorously mixed, and centrifuged. The combination of phenol and chloroform leads to the formation of a two-layered system. In this system, DNA migrates to the upper aqueous layer, while proteins and lipids move to the lower organic layer (Figure 1). By isolating DNA in this way, researchers could achieve relatively pure samples marking a significant advancement in early genetic studies [9].

Following the separation phase, multiple wash steps are performed to remove residual contaminants ensuring the DNA is free of proteins and other impurities [10]. While this method yields high-quality DNA it does not necessarily produce high DNA concentrations making it less effective for samples with very low DNA content. The labor-intensive and time-consuming nature of phenol-chloroform extraction, along with its low throughput, limits its suitability in high-demand forensic and clinical laboratories. However, due to its reliability in generating pure DNA samples, it remains a gold standard in laboratories focusing on molecular biology and early-stage research [8].

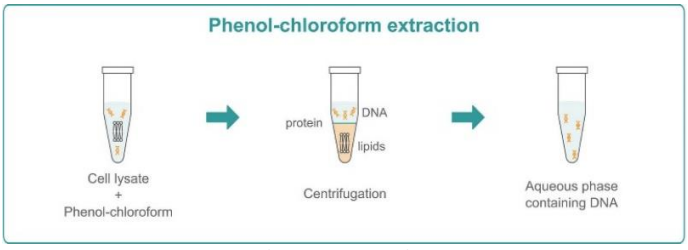


Fig. 1. Procedure of Phenol-Chloroform Extraction [11]

Despite its utility, the phenol-chloroform method is not without significant drawbacks. Both phenol and chloroform are hazardous with phenol being particularly corrosive and toxic to skin and chloroform being a potential carcinogen [9]. Their use requires strict safety precautions such as working under a fume hood and using personal protective equipment. The environmental impact of disposing of these chemicals has also led to the development of alternative DNA extraction methods that are safer and more efficient such as the silica-based spin column and magnetic bead techniques [10]. Today, although the phenol-chloroform extraction method is largely replaced in routine applications it remains relevant for specific research contexts where sample purity is a priority.

### B. Salting-Out Method (1987)

The salting-out method developed as a safer alternative to phenol-chloroform extraction utilizes high salt concentrations to isolate DNA without the hazards associated with organic solvents. In this method, cells are first lysed in a solution containing a high concentration of salt which helps break down cellular structures and release DNA and other cellular materials. When the mixture is centrifuged, the salt binds to proteins causing them to aggregate and precipitate out of the solution leaving the DNA in the aqueous (supernatant) phase. This approach makes DNA extraction more accessible and environmentally safer as it reduces exposure to toxic chemicals [12].

In addition to being safer, the salting-out method is relatively straightforward and is suitable for high-throughput applications making it popular in laboratories that process large sample volumes such as clinical and forensic labs [13]. Compared to phenol-chloroform extraction it requires fewer safety precautions and is generally faster allowing for quicker processing times and greater efficiency. After centrifugation DNA in the supernatant can be easily collected typically by adding ethanol or isopropanol to precipitate the DNA followed by a final wash to remove any remaining salts. The simplicity of this method makes it adaptable to various DNA extraction protocols including automation which is crucial in settings where high sample turnover is essential.

### C. Silica-Based Methods (1990s)

The silica-based method, commonly known as the spin-column method transformed DNA extraction processes in the 1990s by providing a quick and efficient alternative to earlier techniques. This method relies on the principle that DNA strongly binds to silica surfaces when chaotropic salts that disrupt hydrogen bonding are present [14]. In practice, a sample containing cell lysates is passed through a silica column where DNA adheres to the silica membrane while other cellular components such as proteins and lipids, do not (Figure 2). This selective binding of DNA makes the silica-based method remarkably efficient and reliable allowing for higher purity and better preservation of DNA integrity compared to earlier methods.

One of the main advantages of the silica-based extraction method is its streamlined process which involves multiple wash steps to remove impurities followed by a final elution step in which DNA is released from the silica membrane. This



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simplicity and the relatively quick extraction time have made it popular in various applications including forensic science, diagnostics, and molecular biology research [15]. Since the process can be completed within minutes, it is ideal for high-throughput settings where speed is essential. Moreover the method's adaptability to automation has further increased its use in laboratories with high sample volumes, such as in clinical diagnostics and genetic testing labs.

The high purity and efficiency of the silica-based method make it particularly suited for applications requiring high-quality DNA, such as PCR amplification, sequencing, and DNA profiling in forensic science. While it is generally more expensive than other DNA extraction methods, the high yield and purity of DNA obtained often outweigh the cost, especially in sensitive applications where contamination-free DNA is crucial [14]. The method's popularity continues today, as it provides a reliable, user-friendly, and high-quality solution to DNA extraction needs across various scientific fields.

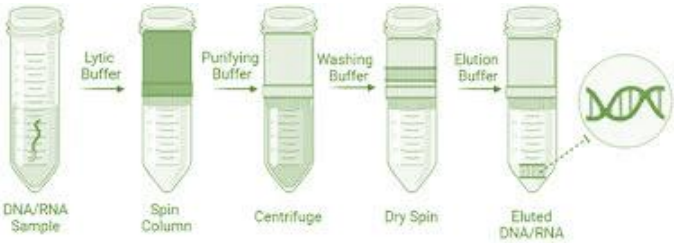


Fig. 2. Procedure of Silica-based DNA Extraction [16]

### D. Magnetic Bead-Based Extraction (1990s)

Magnetic bead-based extraction developed alongside silica-based methods offers a unique approach to DNA isolation by utilizing magnetic particles coated with molecules that bind to DNA. In this process, magnetic beads are added to a cell lysate where they selectively attach to DNA molecules. When a magnet is applied the DNA-bound beads are separated from the lysate leaving other cellular components behind. This step is followed by a series of washes to remove impurities and finally the DNA is eluted from the beads to obtain a pure sample. The magnetic bead-based approach minimizes the need for centrifugation and complex handling, making it particularly user-friendly (Figure 3) [15].

One of the major advantages of the magnetic bead-based method is its adaptability to automation which has made it widely popular in high-throughput laboratories especially in fields like forensic and clinical diagnostics where large sample volumes are processed regularly. By allowing easy integration into robotic systems this technique has facilitated streamlined workflows in labs leading to faster and more efficient DNA extraction processes [17]. The reduced handling requirements also lower the risk of sample contamination which is critical in sensitive applications such as forensic DNA analysis and molecular diagnostics where accuracy and purity are paramount.

Despite its advantages, magnetic bead-based extraction has some limitations. The method can be costly due to the price of magnetic beads and the specialized equipment required making it a more expensive option compared to traditional extraction methods like salting-out. Additionally, while it is highly effective for isolating small amounts of DNA the cost factor may limit its use in research settings with budget constraints [17]. Nevertheless, the magnetic bead-based approach remains a valuable tool for DNA extraction due to its versatility, precision, and suitability for automation, particularly in clinical and forensic contexts.

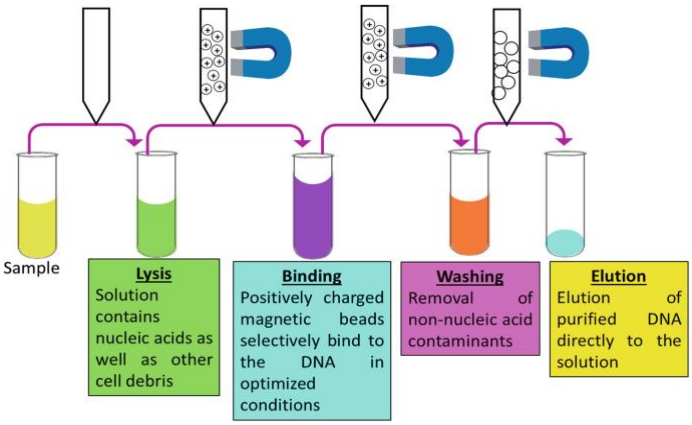


Fig. 3. Procedure of Magnetic Bead-Based DNA Extraction [18]

### E. Chelex 100 Resin Method (1990s)

The Chelex 100 method emerged as a rapid and straightforward technique for extracting DNA, particularly in forensic applications. This method utilizes Chelex resin a chelating agent that binds metal ions to protect DNA during the extraction process. When a sample is treated with Chelex resin and subsequently boiled, the heat disrupts cellular structures, releasing the DNA into the solution. The Chelex resin sequesters metal ions, such as magnesium, which can catalyze the degradation of DNA during extraction (Figure 4). This protective mechanism is especially beneficial in forensic casework, where samples may be small or degraded due to environmental exposure [19].

One of the key advantages of the Chelex method is its rapidity and ease of use. The entire process can often be completed in less than an hour, making it ideal for time-sensitive forensic situations where quick results are necessary. Furthermore, the method is particularly effective for extracting DNA from challenging samples, such as those derived from old or degraded biological materials, which are frequently encountered in forensic investigations [20]. The simplicity of the Chelex method also means that it requires minimal equipment and can be performed with standard laboratory materials, enhancing its accessibility for many forensic laboratories.

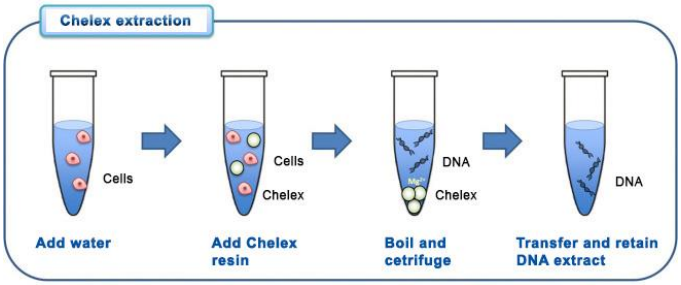


Fig. 4. The procedure of Chelex, DNA Extraction [21]



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However, while the Chelex 100 method is advantageous for speed and handling of degraded samples, it does not yield the highest purity of DNA. The extracted DNA may contain contaminants that can inhibit downstream applications, such as PCR amplification or sequencing, which require high-quality DNA for accurate results [19]. As a result, the Chelex method is often used as a preliminary extraction technique, with additional purification steps necessary for applications demanding greater purity. Despite these limitations, the Chelex method remains a valuable tool in forensic science, providing an effective solution for extracting DNA from challenging samples in a timely manner.

### *F. Automated Extraction Systems (2000s)*

Automated systems have significantly transformed DNA extraction processes by streamlining and standardizing the workflow, making it more efficient and reliable. These systems integrate multiple steps of the DNA extraction procedure—such as cell lysis, washing, and elution—into a single automated workflow. By utilizing sophisticated robotics and software, automated DNA extraction equipment can handle numerous samples simultaneously, reducing the time and labor required compared to manual extraction methods. This automation minimizes human error and ensures consistency across samples, which is crucial in applications such as clinical diagnostics and forensic analysis, where accuracy is paramount [22].

In high-throughput laboratories, the ability to process samples in a closed system with pre-programmed steps has revolutionized DNA extraction. These automated systems allow for the efficient handling of large volumes of samples, making them ideal for settings where speed and productivity are essential. For example, in forensic laboratories, where timely DNA profiling can be critical to investigations, automated extraction systems can rapidly prepare samples for analysis, significantly reducing turnaround times [23]. Moreover, the closed-system design of these platforms helps to minimize contamination risks, further enhancing the reliability of the extracted DNA.

While automated DNA extraction systems provide numerous benefits, including improved efficiency and reduced operator variability, they can also entail higher initial costs and require specialized training for laboratory personnel. Additionally, some automated systems may be limited to specific types of extraction protocols, which could restrict their versatility in different research or clinical applications [22]. Nevertheless, the adoption of automated systems in forensic and diagnostic laboratories continues to grow, as they offer a practical solution to meet the increasing demand for rapid and consistent DNA extraction methods, ultimately supporting advancements in genetic research and forensic science.

Fig. 5. Steps performed within the Automated DNA Extraction System [24]

### *G. Microfluidic-Based Extraction (2010s)*

Microfluidic DNA extraction represents a cutting-edge advancement in DNA analysis by utilizing lab-on-a-chip technology to perform extraction on a miniature scale. This innovative approach allows for the integration of various DNA extraction steps—such as cell lysis, purification, and elution—within microchannels etched onto a small chip. By doing so, microfluidic systems significantly reduce the volume of reagents needed, minimizing waste and lowering costs associated with DNA extraction [25]. Moreover, the precise control of reagents and sample handling within these microchannels enhances the efficiency of the extraction process, allowing for quicker turnaround times compared to traditional methods.

One of the key benefits of microfluidic DNA extraction is the ability to work with smaller sample sizes, which is particularly advantageous in situations where sample availability is limited or when dealing with precious materials, such as forensic evidence or rare biological specimens. This scalability makes microfluidic systems ideal for portable and rapid DNA analysis, particularly in field-based applications such as forensic investigations and environmental monitoring. For instance, in forensic science, the ability to quickly analyze DNA from crime scenes or biological evidence can provide critical information to support investigations [26]. Additionally, microfluidic devices can be designed for ease of use in various settings, making them suitable for point-of-care diagnostics and on-site testing.

Despite its many advantages, microfluidic DNA extraction does come with challenges. The complexity of designing and fabricating microfluidic chips can be a barrier to widespread adoption, and these systems may require specialized equipment and training for effective use. Additionally, while microfluidic methods can provide high-quality DNA extractions, achieving consistent results across different sample types and conditions can be complex [27]. Nonetheless, the potential for rapid, efficient, and portable DNA analysis positions microfluidic DNA extraction as a promising technology for the future of forensic science, clinical diagnostics, and environmental applications.

### *H. Nanotechnology-Based Extraction (2020s)*

Advances in nanotechnology have paved the way for innovative techniques in DNA extraction, particularly through the use of nanoparticle-based methods. These methods enhance the efficiency of DNA binding and purification by utilizing nanoparticles that can selectively attach to DNA molecules. When nanoparticles, often coated with specific ligands that interact with DNA, are introduced to a sample, they bind to the DNA while allowing other cellular components and contaminants to remain in solution [28]. This selective binding capability not only improves the yield of extracted DNA but also facilitates faster purification processes, making it a compelling alternative to traditional extraction methods.

Following the binding process, the separation of DNA from the sample is typically achieved using magnetic or centrifuge-assisted techniques. Magnetic nanoparticles can be easily manipulated with an external magnet, allowing for rapid and

efficient separation of the DNA-bound particles from the rest of the sample [29]. This method simplifies the purification process and reduces the number of steps needed to isolate high-quality DNA. The ability to efficiently separate and purify DNA in a streamlined manner positions nanoparticle-based extraction as a powerful tool in various applications, particularly in forensic and clinical settings where rapid and reliable DNA analysis is crucial.

Although nanoparticle-based DNA extraction is still in its early stages of development, its potential for ultra-sensitive DNA extraction is particularly promising. This technique could significantly enhance the analysis of trace amounts of DNA, which is often the case in forensic investigations involving low-quality samples [30]. Furthermore, the ability to tailor nanoparticles for specific binding affinities and functionalities opens new avenues for customizing DNA extraction processes according to the needs of different applications. As research progresses, nanoparticle-based DNA extraction could revolutionize how DNA is isolated and analyzed, offering new possibilities for diagnostics, forensic science, and beyond.

## IV. Extraction of Touch DNA

DNA extraction techniques have made remarkable progress over the years paving the way for advancements in various applications from genetic research to forensics. One area that has greatly benefited from these advancements, is Touch DNA, the DNA left behind from skin cells when a person touches or comes into contact with an object or surface. This field has become especially relevant in forensic science because it allows investigators to recover genetic material from very small or trace amounts left behind on evidence such as clothing, weapons, and everyday objects [31].

Over recent years, researchers have made significant progress in improving the sensitivity of DNA detection techniques. Modern forensic methods can now detect and analyze extremely small DNA samples, down to a few skin cells. Techniques like Real-Time PCR (qPCR) and Next-Generation Sequencing (NGS) allow for more accurate quantification and analysis of low-level DNA, which is crucial for analyzing trace evidence from Touch DNA samples [32][33].

Specialized collection tools, like swabs made of novel materials or with enhanced absorbency, have improved the efficiency of capturing trace DNA. Techniques such as taping or using vacuum-based collection systems are being explored to capture DNA from difficult surfaces. This variety of collection techniques is essential because different surfaces (e.g., porous, rough, or smooth) affect DNA transfer and retention differently [34].

Environmental factors, such as humidity, temperature, and UV exposure, can degrade DNA samples, which complicates Touch DNA analysis [35]. Ongoing research aims to stabilize DNA at the time of collection or develop preservation methods that can safeguard fragile DNA molecules. For example, using antioxidant stabilizers or lyophilization (freeze-drying) techniques can potentially maintain DNA integrity until it reaches the lab.

Since Touch DNA often involves complex or mixed samples with low quantities of DNA, forensic scientists are working to improve the reliability of interpretation using probabilistic genotyping software. These algorithms can help interpret complex mixtures, even with low-level or degraded DNA, by generating statistical models that estimate the likelihood of specific contributors to a DNA sample [36].

A significant part of Touch DNA research investigates the mechanisms of DNA transfer and persistence. Researchers are studying factors such as the amount of pressure applied, the duration of contact, and the type of surface to understand how DNA is transferred, how long it remains detectable, and the likelihood of secondary transfer (DNA transferred to an object by indirect contact). These studies are helping to refine interpretations of Touch DNA evidence and reduce the chances of false leads.

### *A. Limitations and Challenges*

Touch DNA often yields very low quantities of DNA, which may not be enough for reliable profiling, especially if the sample has been exposed to degrading conditions [37]. Many Touch DNA samples contain DNA from multiple individuals, making it difficult to interpret the genetic profile accurately. DNA can be unintentionally transferred from one person to an object or surface through an intermediary (secondary transfer), leading to misleading results. For example, DNA from someone who has never touched an object might appear on it if transferred indirectly. Trace DNA samples are susceptible to contamination, which can alter or obscure the results.

### *B. Future Extraction Techniques Needed for Effective Use of Touch DNA*

New nanotechnology-based extraction techniques that use nanoparticles to capture even trace amounts of DNA could significantly improve the yield from Touch DNA samples [38]. Targeted amplification techniques, such as those that use unique primers specific to highly abundant or informative DNA regions, could enable more robust profiles from low-yield samples [39]. Microfluidic chips are also promising for ultra-sensitive extraction, allowing for highly efficient DNA processing on a miniature scale with minimal sample loss [40].

Improved collection devices that are better at picking up small quantities of DNA from various surfaces, such as flexible micro-sponge swabs or adhesive tape optimized for DNA retention, would enhance initial DNA capture. Developing concentration techniques to enrich low-yield DNA samples, such as using filtration or centrifugation, would ensure that even minute samples contain enough DNA for analysis.

For cases where Touch DNA yields very few cells, single-cell analysis techniques like laser capture microdissection (LCM) can isolate individual cells or cell groups for analysis. This method, combined with Whole Genome Amplification (WGA), could make it possible to obtain DNA profiles from a single cell, minimizing the issue of low yield [41].

Machine learning algorithms and advanced probabilistic genotyping could further aid in interpreting complex mixtures. These systems can predict the most likely contributors, even in highly mixed or low-quality samples, reducing ambiguity and aiding in clearer analysis. Multi-omic approaches, which

integrate additional molecular data (like RNA or protein analysis), may also be helpful in distinguishing individual contributors in DNA mixtures [42].

Developing compact, portable DNA analysis devices that allow for on-site Touch DNA analysis would speed up the investigative process, especially in time-sensitive cases. Miniaturized devices could use microfluidics and rapid PCR techniques to enable real-time DNA profiling directly at crime scenes.

Research on the mechanisms of DNA transfer will be essential in refining forensic interpretations of Touch DNA. Establishing standardized protocols and thresholds for evaluating transfer likelihood, persistence, and degradation will help forensic scientists understand and account for secondary or tertiary DNA transfer.

## V. Discussion

The landscape of DNA extraction has transformed dramatically, from the early labor-intensive phenol-chloroform technique to sophisticated nanotechnology-based methods. Each method has contributed uniquely to the toolkit available for molecular and forensic biologists, though each comes with limitations in terms of sample type, purity, and ease of use. As forensic science increasingly relies on trace samples like touch DNA, challenges such as low yield, contamination risk, and degradation complicate the extraction process. Newer methods like microfluidic and nanotechnology-based techniques are pushing the boundaries of sensitivity and purity, showing promise for challenging forensic samples. Despite these advances, limitations remain, especially in standardizing these methods for routine forensic use.

Looking to the future, DNA extraction techniques are expected to evolve further, focusing on enhancing sensitivity, minimizing contamination, and reducing processing time. Technologies like artificial intelligence and machine learning may play a role in optimizing extraction protocols for specific sample types. Innovations in nanotechnology and automation will be crucial for forensic and clinical applications, potentially leading to more reliable and efficient DNA extraction, particularly for touch DNA.

DNA extraction has several current and future challenges that necessitate innovative solutions to overcome the limitations of existing methods. One of the foremost areas of improvement is ultra-sensitivity and trace DNA recovery. As forensic analysis requires the recovery of extremely small amounts of DNA, future extraction techniques must enhance sensitivity and efficiency. This will enable the extraction of high-quality DNA from minute and often degraded samples, which is critical for accurate analysis in various contexts.

Another significant challenge lies in developing non-invasive and field-compatible methods. There is a growing demand for portable and user-friendly DNA extraction devices suitable for on-site analyses, particularly in wildlife studies, environmental monitoring, and forensic investigations. Techniques that minimize sample handling and reduce dependence on sophisticated laboratory infrastructure will be essential to meet these needs.

The integration of DNA extraction techniques with sequencing technologies, such as next-generation sequencing (NGS) platforms, is crucial. Methods that allow direct integration without the need for further purification could significantly reduce processing times, enhancing capabilities for real-time disease monitoring and pathogen detection.

There is a pressing need for eco-friendly and sustainable methods in DNA extraction. Many current techniques utilize harmful chemicals and disposable plastic components, raising concerns about environmental impact. Developing greener extraction methods that are cost-effective for high-volume use will be vital in addressing these environmental challenges.

As DNA extraction technologies continue to evolve future methods are expected to prioritize miniaturization, sensitivity, environmental sustainability, and compatibility with emerging molecular analysis techniques. These advancements will not only enhance the precision and practicality of DNA extraction but will also support a wide range of applications across forensics, medicine, and scientific research.

## VI. Conclusion

DNA extraction methods have come a long way since the discovery of the double helix structure of DNA in 1953. Recent advancements in technology and molecular biology have led to the development of numerous innovative and efficient DNA extraction techniques. These methods have the potential to revolutionize various fields, including medical diagnostics, forensic investigations, and biotechnology.

Moreover, the integration of automation, robotics, and microfluidics into DNA extraction processes has facilitated the high-throughput and cost-effective extraction of DNA samples. Additionally, the use of non-invasive and non-destructive DNA extraction methods has increased the feasibility of obtaining genetic information from a variety of sample types.

Despite the significant progress made in DNA extraction methods, there are still challenges and limitations to overcome. These include the need for standardization of extraction protocols, the development of techniques that can handle low-quality and degraded DNA samples, and the reduction of interference from inhibitors and contaminants.

Overall, with the continuous efforts of scientists and researchers, it is expected that DNA extraction methods will continue to evolve, resulting in faster, more efficient, and more accurate DNA extraction methods. This will have far-reaching implications in various fields and contribute to a deeper understanding of genetic information, ultimately leading to improved human health and well-being.

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