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Forensic Science International: Genetics 74 (2025) 103171

Contents lists available at ScienceDirect

Forensic Science International: Genetics

journal homepage: www.elsevier.com/locate/fsigen

Improving the forensic genetic workflow for countries with small geographical areas: What are the options and how cost effective are they?

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ARTICLE INFO

Keywords:
Forensic laboratory
Business case
Rapid DNA
Developing country
Satellite laboratory
Sample screening

ABSTRACT

Forensic services worldwide often encounter considerable challenges relating to funding and infrastructure. Smaller jurisdictions or areas where forensic resources are scarce are faced with complicated choices in how they approach criminal casework, with a number of options available. Often these involve trade-offs between cost, time and data quality. Faced with such decisions it becomes important for the field to acknowledge the realities facing such jurisdictions, discuss the pros and cons of each approach, and identify a framework for making such decisions. This novel paper, reviews the available literature and identifies three main solutions for consideration: 1) the use of satellite laboratories for sample triage, 2) the use of a main regional laboratory for full forensic analysis and 3) the use of rapid DNA by police for reducing backlogs. Alongside these strategies, the impacts of cost and quality in regard to each of the stated options are considered. While the literature supports the assertion that some methods can reduce downstream costs via the reduction in turnaround times, there is limited data highlighting the business case used to support decision making when considering these options including the use of cost:benefit analyses or case studies, emphasizing the novelty of this paper. This is likely due to the commercialized nature of the forensic sector preventing the publication of a private laboratory's business approach. The lack of emphasis on the 'business case' in forensic literature has the potential to mislead R&D scientists who may consequently fail to consider such factors when performing their own research.

1. Introduction

In recent years, the increasing application of science-based methods within the criminal justice system has elevated the importance of forensic science. Extensive evidence underscores the value of forensic investigations and the necessity of investing in these capabilities [56]. Forensic analysis plays a dual role: it aids in prosecuting offenders and exonerating the innocent, while also serving as a deterrent to crime [47]. However, not all countries can keep pace with advances in forensic science due to variations in size, accessibility, infrastructure, funding and crime rates.

Smaller jurisdictions face distinct challenges compared to larger, similarly developed regions, such as limited access to trained personnel, consumables and equipment in addition financial constraints [6]. For example, the tropical climate in Seychelles affects the effectiveness of fingermark detection dyes [5], and supply chain disruptions have necessitated alternative formulations of carrier solvents to maintain budgets without sacrificing quality. Larger, less developed areas can also face similar issues, as a country's economic development does not always correlate with the sophistication of its forensic services [57]. This link can be visualized in Fig. 1.

Additionally, many developed nations struggle with inefficient forensic services, while some underdeveloped countries boast sophisticated systems. Understanding local infrastructure enforcement mechanisms and administrative structures is critical in determining the most suitable forensic workflow for a given region. Strategies range from in-house analysis, such as local police laboratories using Rapid DNA, to outsourcing evidence to satellite or regional laboratories [14]. This paper focuses on resource-constrained small jurisdictions, recognizing that size alone does not imply a lack of financial resources or development. Economies of scale play a crucial role in understanding the differences between smaller and larger forensic laboratories. Larger laboratories can often spread costs—such as those for equipment, accreditation, and staffing—across higher volumes of casework,

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https://doi.org/10.1016/j.fsigen.2024.103171
Received 18 July 2024; Received in revised form 15 October 2024; Accepted 30 October 2024
Available online 8 November 2024
1872-4973/

resulting in lower per-sample costs. In contrast, smaller laboratories must bear the same high setup and operational costs but process fewer cases, making cost efficiency more difficult to achieve [25]. This disparity emphasizes the importance of carefully selecting forensic workflows for smaller jurisdictions, where limited resources and infrastructure necessitate greater financial caution.

All forensic workflow models present challenges in maintaining accreditation, best practices and quality results. In-house analysis, within a police laboratory, may be favorable when taking into account the sensitivity of certain sample types, such as biological evidence which is highly susceptible to degradation [19]. Being able to analyze the evidence quicker, with less transportation, could reduce the risk of contamination and provide a quicker turn-around time of results [30]. This in turn allows for quicker convictions and reduced taxpayer money being spent on custody suites as well as greater control over the full process. Nonetheless, the set-up of a dedicated forensic police laboratory can be vastly expensive without the accessibility of existing infrastructure or government funding.

There seems to be an overarching economic problem surrounding forensic laboratories and their provisions in general, across the globe [25] This is illustrated as the allocation of limited resources without compromising the quality of results, as the demand for these services increases. Initial start-up costs associated with a laboratory set-up are undoubtedly high. Moreover, costs corresponding to accreditation, staffing, training, governance and administration are all to be considered [41]. A study that investigated forensic toxicology in Malta identified the country had three key issues, financial feasibility, the lack of an overlooked national laboratory and the difficulty in finding proficient staff [4]. Many jurisdictions may find in-house analysis financially unfeasible, though alternatives like Rapid DNA within police stations may offer a practical solution without an extensive set-up, although initial investments can be high.

Outsourcing evidence to satellite laboratories presents a viable option for smaller jurisdictions lacking specialized expertise. Within the niche of certain sample types, it becomes difficult to find specialists such as forensic DNA or gunshot residue analysts. A lack of specialized training can compromise the integrity of the analysis and the whole investigation. As such, it would be necessary to outsource evidence to a centralized laboratory to ensure the analysis is carried out correctly and to a high standard as such to be admissible in a court room [1]. It is imperative that all forensic analyses be carried out without bias and outsourcing to a provider is a way of ensuring impartiality as they remain liable for keeping within a set of quality standards [46]. While outsourcing can reduce the cost of maintaining laboratory equipment and accreditation, it introduces concerns about losing control over the process and incurring additional expenses, such as travel and security for evidence transport [3]. It is also possible that this workflow presents additional costs that could be better seen invested in an in-house analysis route that would bring about an increased return on investment [33]. Screening samples before outsourcing, particularly for low-yield DNA samples, can help minimize costs by limiting unnecessary analysis. This is further detailed in the paper.

There is considerable literature on the broad concepts of outsourcing and in-house forensic analysis, but recent studies addressing their application to smaller jurisdictions are scarce. This review aims to fill this gap by evaluating potential solutions and their cost-effectiveness. Literature for this paper selected using ‘forensic laboratory’, ‘small jurisdictions’, ‘rapid DNA’, ‘satellite laboratory’ and ‘police laboratories’ with additional keywords related to business perspectives, including ‘cost-benefit’, ‘cost savings’, ‘return on investment’ and ‘business case’. The aim of this paper is to briefly identify these discrepancies and examine practical solutions such as the use of rapid DNA, in-house police laboratories and satellite laboratories to perform forensic analyses at a cost-effective rate. The novelty of this paper lies in applying established forensic science challenges to the context of smaller jurisdictions, providing practical, cost-effective strategies for forensic analyses.

2. Satellite laboratories

When considering different models used to describe forensic laboratory workflows, three are commonly employed (Fig. 2). Within abundant nations, workflow A is prevalent where a network of

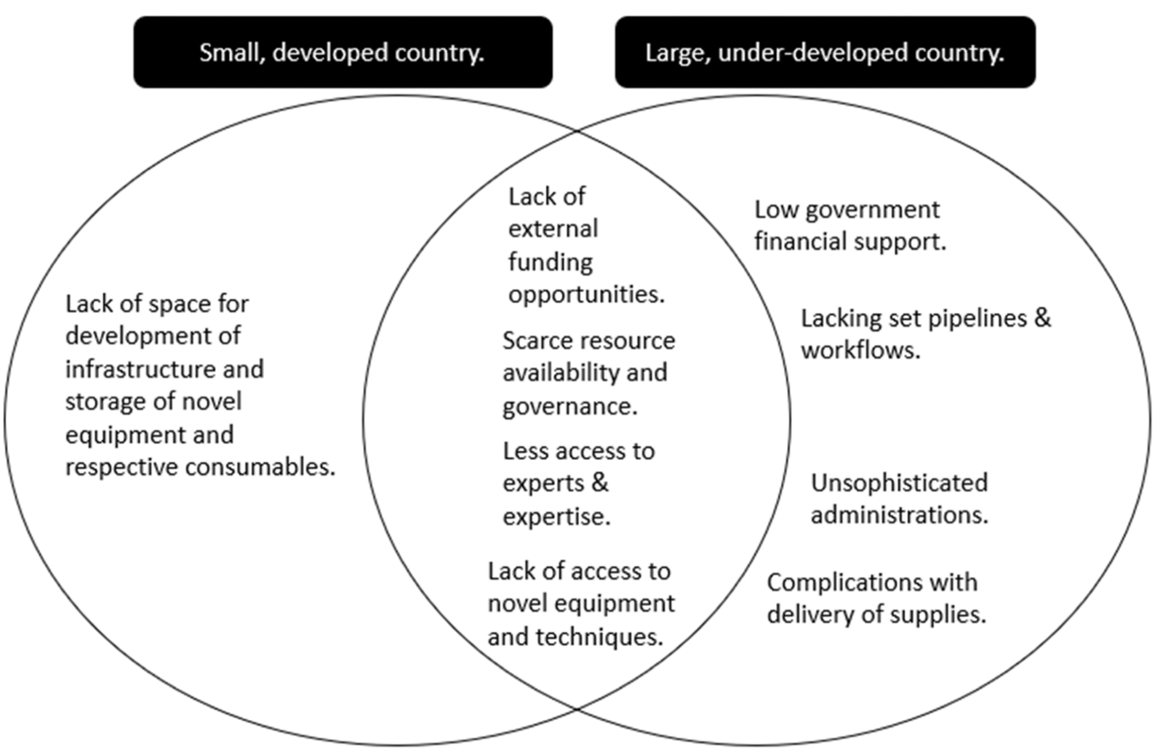

Fig. 1. Venn diagram illustrating the common challenges faced by small and underdeveloped countries.

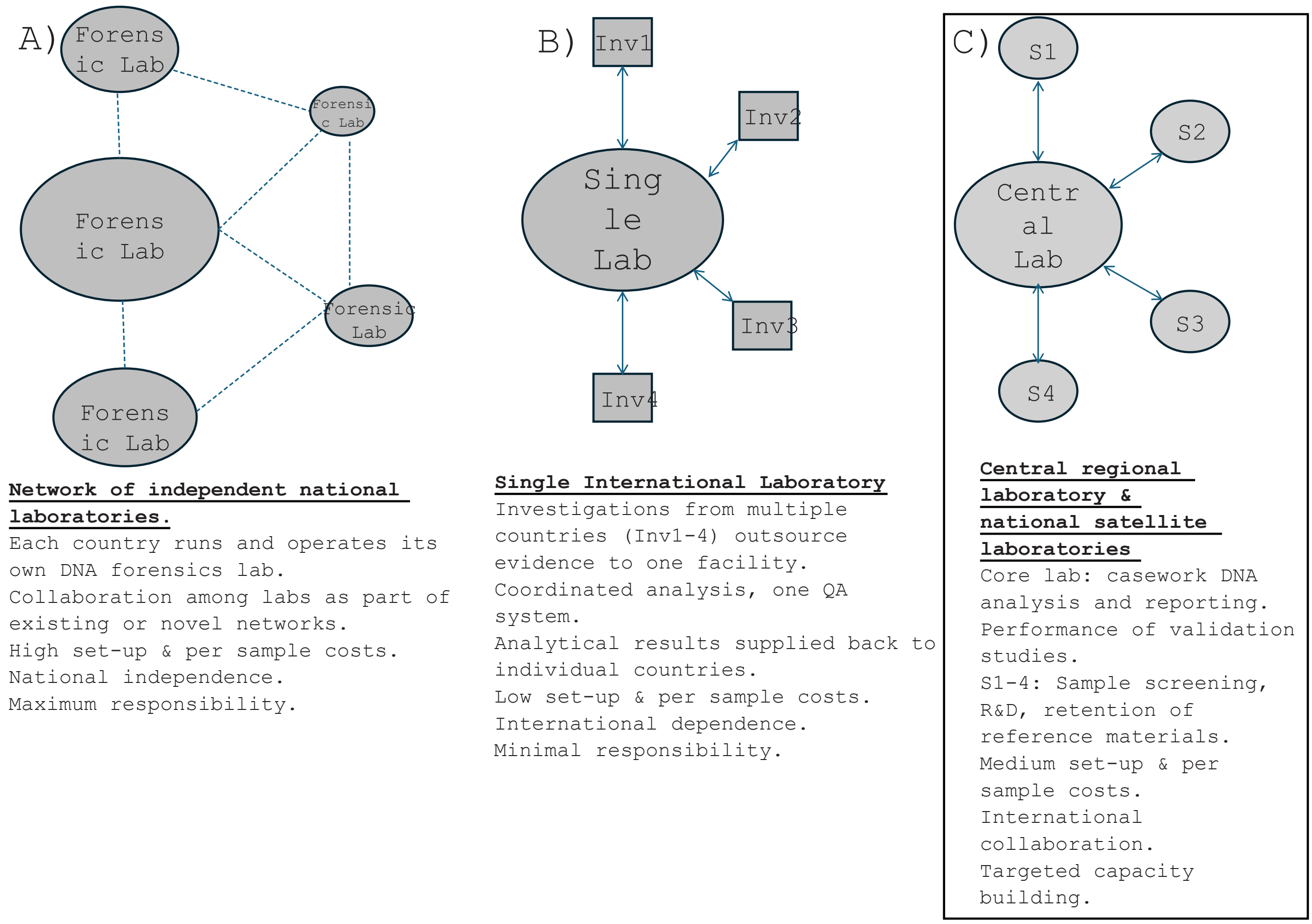

Fig. 2. The workflow of 3 potential laboratory models. A) shows a dedicated forensic laboratory in each country. The varying sizes highlight the capacity of different countries. B) portrays smaller countries or those with fewer resources outsource their evidence items to a larger accredited laboratory that is likely outside of the country. C) shows DNA sample screening may occur in-house initially with those samples needing further analysis again to be outsourced to an accredited laboratory out of the country. Whilst satellite laboratories can undertake multiple forensic disciples, our main focus here is on DNA analysis and such this has been highlighted here. Figure edited from [42].

laboratories conducts the full spectrum of forensic analysis (Fig. 2A). This model is observed in Western European countries such as the United Kingdom, France and Germany. In contrast, smaller jurisdictions with limited resources tend to rely on workflow B where samples are outsourced to large forensic laboratories in different countries (Fig. 2B), as seen in smaller geographies such as Gibraltar, the Republic of Cabo Verde, The Seychelles, Guernsey, The Channel Islands and the Isle of Mann. Additionally, the Pacific Islands nations experience issues with isolation, limited infrastructure, and frequent natural disasters, which impact forensic operations. Their small forensic teams often rely on international partnerships for complex analyses as well as sending their own workers to Australia for training [2].

Another example is The Falkland Islands. Due to its small population and remote location, the islands rely on the UK for many services, including forensic analyses, leading to delays and high costs. The International Committee of the Red Cross (ICRC) carried out several humanitarian projects in The Falkland Islands in 2021 to identify Argentine soldiers that were buried. Some human remains were carefully sampled in a temporary laboratory built on-site and managed by the ICRC due to insufficient expertise within The Falkland Islands themselves. Samples were then outsourced to Argentina for full analyses. The project included multiple international collaborations, including Switzerland, the United Kingdom and Argentina [17].

Workflow C offers an intermediate approach, where preliminary analyses are conducted in smaller, domestic satellite laboratories, with more complex tests outsourced to larger accredited facilities abroad (Fig. 2C) [29,38]. This model is employed in places where some infrastructure is available, enabling faster local processing of samples [16]. In the United States of America, for example, state forensic laboratories coexist with satellite laboratories, some located in medical centers and universities, making use of all three workflows [51]. While satellite laboratories can support various forensic disciplines this paper focuses specifically on DNA analysis.

In some instances, cross-border forensic collaborations present a viable alternative to domestic satellite laboratories, especially for countries with limited forensic infrastructure. Countries within the European Union, for example, benefit from frameworks that facilitate cross-border cooperation in forensic services, which can be more cost-effective for smaller jurisdictions. However, these arrangements present challenges related to jurisdictional differences, legal standards and logistics [40]. International accreditation, such as ISO17025, is crucial in ensuring consistency and reliability across borders, promoting seamless collaboration [44]. This becomes especially important when considering the increasing prevalence of cross-border crimes, where forensic evidence collected in one country may need to be analysed in another [14]. These cross-border systems offer an alternative solution for countries that lack domestic forensic laboratories but may require the establishment of international agreements and alignment of legal standards to be fully effective.

It is also worth noting Bhutan's experience. Bhutan previously outsourced forensic evidence to the UK and India, but in 2023, they made the decision to establish an in-house forensic laboratory with the support of Cellmark and funding from the Austrian Development Agency (Cellmark Forensic Services, 2024). This shift was driven by the long turnaround times and high costs associated with outsourcing. This demonstrates the importance of international cooperation for small jurisdictions and highlights how developing countries often face logistical and financial barriers in maintaining their own forensic capabilities. However, while the physical infrastructure is now in place, Bhutan still faces challenges in terms of training personnel. Furthermore, Bhutan must now convince the Royal Court of Justice to accept DNA evidence in legal proceedings [15]. This situation mirrors the broader challenges that small or developing jurisdictions face when adopting modern forensic technologies: even after establishing infrastructure, there is often a lag in gaining legal and societal acceptance for new forensic methods.

2.1. Sample screening through an accredited satellite laboratory

Despite the obvious benefits of model C to countries with small geographic areas there have been few attempts to develop bespoke forensic satellite laboratories from the ground up due to the costs associated with such an endeavor. Most often, existing facilities are identified that can be shared or co-opted for forensic application such as hospitals or veterinary labs. These facilities perform their own non-forensic analysis, have an existing workforce, instrumentation, and quality assurance processes in place so much of the organizational burden is lifted. A working example of this in a small country can be seen in Malta where their forensic pathology services are carried out at a university hospital [9]. Further examples exist in Malawi where the Government Central Veterinary Laboratory is providing the space and the quality assurance framework to begin testing forensic testing seizes of illegally trafficked wildlife (R Ogden 2023, personal communication).

The purposes of such accredited satellite laboratories are not to provide the complete bioanalytical pipeline but to simply ease the cost and time burden associated with traditional outsourcing. Consequently, they often still require the support of a larger laboratory for the final result. For DNA evidence, the sample may undergo examination, extraction and quantification in the satellite lab before being sent for STR analysis or DNA sequencing. The real benefit of this method is that the process allows sample triage whereby the choice to send the sample for further analysis at another location is made by the Investigating Authority after discussion with the local satellite laboratory based on objective data. For example, if no DNA is detected the sample would not be sent for analysis which becomes a cost-saving measure through not paying for STR profiling and the analysis of a blank sample. Other potential savings include reduced sample transport costs, time savings and faster casework resolution for samples non-selected for further analysis.

Despite the positive attributes outlined above, there are also negative issues to be considered associated with the use of a satellite laboratory. For example, there are still costs corresponding to the upkeep of these services as well as staffing and their training requirements. It may be more difficult to find specialized personnel in smaller jurisdictions due to the lack of resources so it may be necessary to bring expertise in to teach and train those that are to work at the laboratory [6]. Also, it is likely that there would be a limited scope whereby only a small range of sample types could be analyzed comprehensively [11].

2.2. Sample screening through a university laboratory

At some level a decision must be made regarding the presence or absence of forensic provision in small geographical areas. Due to the costs of setting up a national or satellite lab and the complexities associated with providing a quality service, is it ever justifiable and ethical to offer zero forensic services? In other words, just because a 'gold standard forensic approach' can't be offered does it logically follow that nothing should be offered? Laboratory accreditation is highly valued in forensic science where strict quality standards help ensure data confidence. However, university laboratories often have the same equipment and expertise to offer, albeit in an unaccredited capacity. While the use of such facilities presents a risk, this pipeline is often the more affordable approach [49].

One of the more paramount concerns associated with a non-accredited laboratory would be that results developed at this facility may not be admissible in court and will be more susceptible to legal challenges by the opposing council. Whilst results will still be beneficial to the criminal investigation in the guidance of crime scene investigators and police officers, any evidence they wish to use in court may need to undergo confirmatory analysis at an accredited laboratory, in which case the outsourcing of this evidence would eventually be inevitable [32]. Moreover, the lack of accreditation status could potentially follow through to a lack of accountability and oversight, as Fig. 3 below demonstrates. This in turn could pose the risk of unreliable and possibly inaccurate results due to a lack of standardization. Nevertheless, oftentimes these screening services implement relevant quality control measures themselves in order to mitigate these risks [34]. Additionally, despite the methods and equipment not being validated, ensuring that staff are qualified and appropriately trained to a high standard will further aid the reduction of said risks and aid bias mitigation [13].

A possible compromise would be to offer a non-accredited screening service where there are multiple sub-samples collected from the scene (i.e., multiple swabs taken from the same pool of blood). In such instances providing a single 'research' sample to a university for screening would not prejudice the case and could provide forensic intelligence to help support investigative decisions. A hypothetical pipeline for this service is detailed in Fig. 4.

Such a strategy circumvents the need for accreditation, which can be time consuming, costly and require additional quality assurance measures such as proficiency testing and documented training [35]. A further benefit of the model is that it allows post-graduate students researching the field of forensics to become more involved and proficient in handling real evidential samples providing hands-on casework experience [10] with local students gaining forensic knowledge which can then be applied to further advancements the country may implement in the future [48]. It may also be beneficial for crime scene investigators to learn about the laboratory procedures and basic techniques to better understand the importance of their side of the investigation such as the collection and preservation of evidence [37]. This could increase awareness and exposure in the field of forensic science, potentially bringing in a greater number of students that can then go on to aid their country in the future [20]. Fig. 5

Technology can significantly enhance knowledge sharing and collaboration among university laboratories and other entities such as forensic service providers and police forces. Advanced communication platforms, secure data storage, and collaborative tools enable real-time data sharing and joint analysis.

3. Police labs and Rapid DNA

3.1. Police labs

More recently, there has been a growing utilization of police laboratories as an alternative to traditional, independent forensic laboratories. This is highlighted in the United Kingdom, especially since the privatization of forensic laboratories [31]. There is literature demonstrating that police laboratories, within the agencies themselves, offer multiple benefits that contribute to their growing appeal. This is illustrated in Fig. 3 whereby a dedicated police laboratory is shown to offer the greatest quality assurance potential, though coupled with a high cost. Fig. 2A additionally highlights the independence of dedicated laboratories combined with maximum responsibility. Similarly, Fig. 5 below presents a simple pipeline of this system merging a forensic

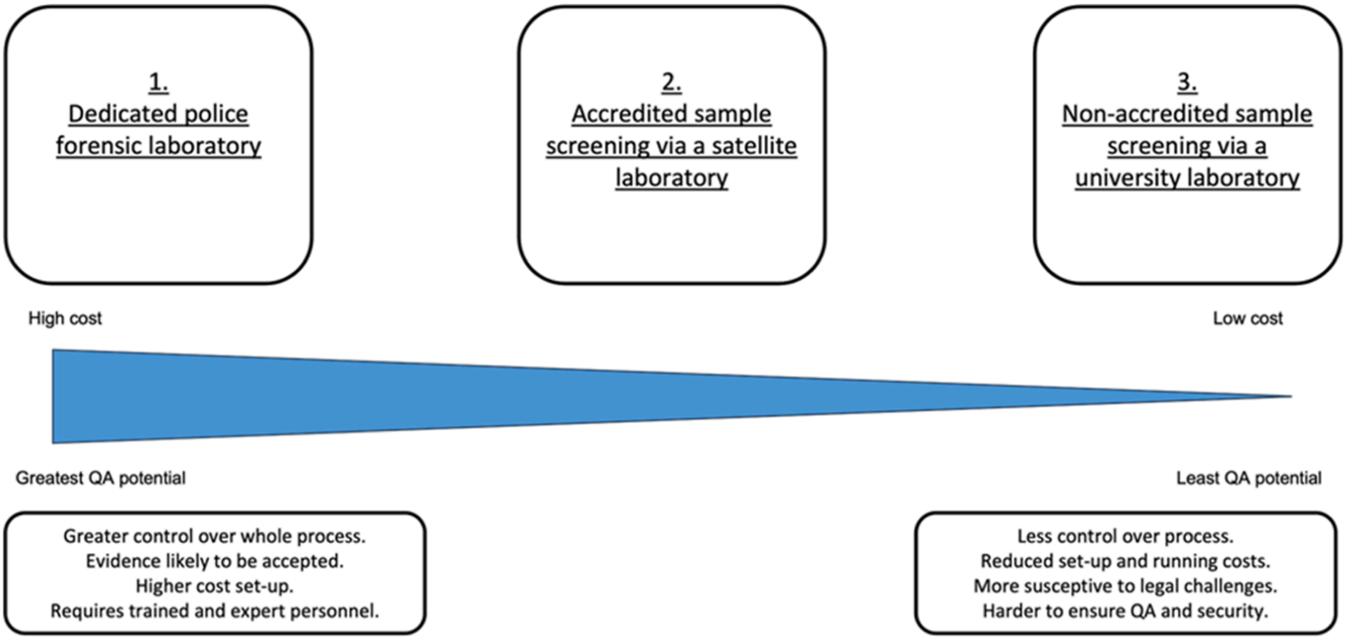

Fig. 3. Summary of three possible DNA analysis laboratory models and their key characteristics. Figure edited from [42].

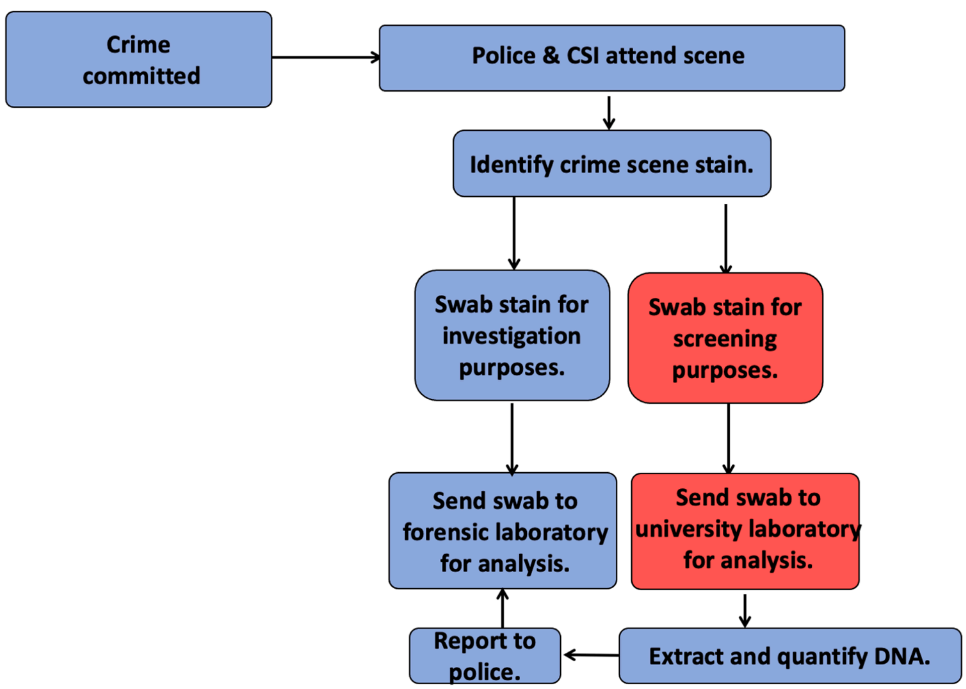

Fig. 4. A hypothetical pipeline setup where a secondary swab is taken at the crime scene in order to perform screening and triage at a local university laboratory.

laboratory and a police station.

This setup allows for greater flexibility due to the close working practices of the laboratory personnel and the police staff. Internal discussions can be had at short notice increasing control over prioritization of samples and the allocation of resources which in turn can lead to faster analysis and prosecution [51]. Furthermore, greater feedback is ensured throughout the analysis process due to the proximity of investigators and scientists within the station. There may be additional savings available if a stop at quant service is offered. As described previously, sample screening is comprised of DNA extraction and quantification, should the level of DNA amount to less than the threshold needed for STR analysis then this information could be relayed back to the investigating officers. At this point, alongside expert advice from the scientists, it may be more cost-effective to discard the sample from further analysis. That being said, it isn't always feasible to remove one sample from a well plate of 96, in the middle of a qPCR run.

There is also potential for crossover of personnel as well as equipment sharing and collaborations which can lead to cost savings. For smaller jurisdictions with limited funds, this becomes a key advantage as it may allow for the allocation of resources to other vital areas within society. Although, the use of police laboratories is beginning to raise some concerns within the world of forensic science. An important aspect in all forensic investigations is the ability to produce objective and impartial results. Therefore, conflicts of interest and bias must be

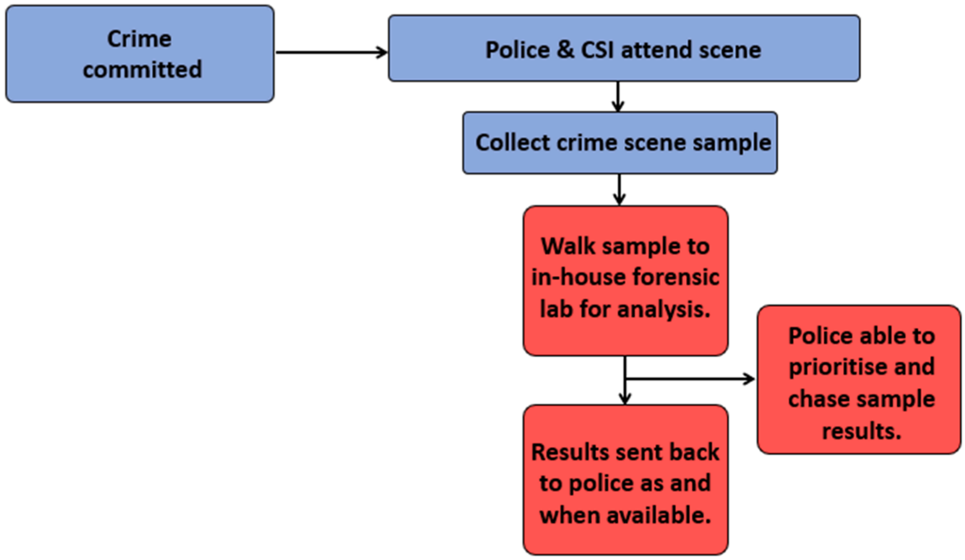

Fig. 5. A hypothetical pipeline setup where an in-house forensic laboratory is set up within the police station to offer full DNA analysis, or sample screening, on site.

mitigated in order to maintain the integrity of the investigation. Having a police laboratory analyze evidence where the same agency is to investigate the crime, may result in potential bias albeit unconscious. Furthermore, it is possible for a hostile work environment to compromise the investigation due to increased pressure to produce favorable results. Where these concerns have previously been challenged in court, they are often dismissed due to the analyst being a scientist and not a law enforcement official and therefore upheld to a code of conduct [26]. Established, independent forensic laboratories tend to have a myriad of experts and dedicated equipment to provide a wide array of analysis across multiple disciplines. However, smaller police facilities may lack this same level of specialization in certain areas of forensic science which could influence the credibility of results [45]. The lack of readily available infrastructure, funds and expert personnel, as declared in Fig. 1, accessible to resource constrained smaller jurisdictions, presents a drawback for such areas considering the use of police laboratories.

3.2. Rapid DNA

Rapid DNA technology continues to develop and has proven to be a beneficial tool in many forensic investigations [39]. Rapid DNA technology can be used to develop a quicker DNA analysis workflow for reference samples, producing results within hours [21]. Where laboratory analysis would need to be carried out by skilled experts, Rapid DNA equipment is said to allow for minimally trained personnel to operate [12]. Whilst it is true that Rapid DNA technology can be integrated within the previously discussed workflows, it can also have benefits when used as a stand alone provision. There have been reports of reference swab STR profiles being provided in as little as 90 minutes [7, 27] and small-scale laboratories are cited as benefitting from the fast turnaround times [50]. An increase in speed of results and a decrease in reference samples sent for laboratory analysis can allow any outsourcing to focus on samples needing specialized analysis. This would lead to better case efficiency and overall speed of solving crimes due to a streamlining of processes [8].

The potential of incorporating Rapid DNA into a reference sample workflow was assessed in Australia [36]. The turnaround time for results via the use of Rapid DNA technology and standard laboratory analysis was compared in relation to crime committed. It was deduced that approximately 480 people per year across the country could be held in custody if reference DNA sample results were produced in real time. The impact of this on the community was highlighted as reducing crime rates due to reoffenders being remanded in custody as well as saving resources because of improved public safety. However, despite this positive result, it was concluded that Rapid DNA was not cost-efficient as a result of current policing policies and sample throughput, although it was expected to remain a viable option in the future. Such discrepancies in data suggest that the application of Rapid DNA may be jurisdiction and geography dependent.

Another limitation to Rapid DNA methods is that they are only currently validated for use on high template reference swab samples due to sensitivity issues. This limits both their application and cost savings. Nevertheless, there have been many attempts to bring Rapid DNA to forensic casework for the analysis of evidence at the scene [55,58]. One of the first successful uses of Rapid DNA in the field occurred during the California wildfires in 2018 to identify victims. It was highlighted that local laboratories were rendered non-functional and lost many resources, whilst distant laboratories became overwhelmed by the influx of samples which can reflect the issues that resource contrsained small jurisdictions constantly experience [18]. Therefore, the use of Rapid DNA technology at the morgue site was implemented. Three ANDE Rapid DNA Identification system instruments were used to analyze human remains with a fourth instrument used for familial reference samples. 89.9 % of samples subjected to this analysis generated DNA results that were then used for familial searches in a matter of hours of sample collection. Furthermore, the research emphasized the importance of generating results at a faster rate in the case of highly degraded remains, in order to better allocate time and resources to those that may provide more successful results. The use of Rapid DNA technologies to combat human trafficking in Costa Rica and Nepal has also been documented [43]. In this research it was established that these countries may not have the resources or infrastructure for large, expensive laboratories yet timely analysis is imperative as perpetrators could flee jurisdictions upon release. Rapid DNA becomes an appealing solution to this discrepancy where results can be produced on the scene and potentially whilst a suspect is remanded in custody.

Overall, Rapid DNA technology may appear to be an attractive tool for resource constrained small jurisdictions due to its convenient usage, speed of results, varying applications, and reasonable accuracy. It would also be essential to consider the fact that the Rapid DNA technology uses the whole sample and therefore must remain limited to those that may be able to be collected again if necessary [28]. Although this is not relevant in every scenario, it may not be too detrimental in smaller jurisdictions where re-swabbing offenders or heading out to a scene would prove easier than in larger areas. Dismissing crime scene samples, it is evident that Rapid DNA can become a useful tool in police stations or at border security for the analysis of reference samples. Minimizing the number of samples sent for outsourced analysis would not only reduce backlogs but may prove to be less costly. There are even reports in the use of Rapid DNA for identifying duplicate samples in DNA databases which would anticipate significant cost savings in certain jurisdictions if this could be realized before sending those reference samples for laboratory analysis [36].

In addition, technological advancements are improving efficiency in the forensic science sector and have the potential to benefit smaller laboratories by enhancing their efficiency and ability to collaborate with larger forensic networks. For instance, smaller jurisdictions can leverage shared databases to cross-reference DNA profiles, thereby accelerating case resolution and reducing dependence on external laboratories. This can also help streamline resources, allowing smaller laboratories to focus on their core strengths while accessing more extensive data from larger systems.

4. Business case development

A business case is essential for identifying optimal strategies to improve forensic services. As the forensic science sector evolves with emerging technologies, it becomes crucial to evaluate potential improvements through a comprehensive business case. This process includes reviewing current workflows, future goals, and conducting a financial analysis to identify the preferred option. Forensic laboratories, regardless of their location, aim to provide high-quality results, but their performance is proportional to available resources [24]. In smaller jurisdictions, these resources are often scarce (Fig. 1), making it necessary to develop a strategy that considers limited financial and infrastructural capacity [59]. A strong business case can guide stakeholders in understanding the benefits and risks of proposed changes, helping to make informed investment decisions.

Despite the critical need for business analysis in forensic services, it remains largely underexplored. Exceptions include initiatives like Project FORESIGHT [25], which provides a performance-based approach to forensic lab efficiency, and the European Quadrupol study [23], which aimed to benchmark forensic laboratory performance. However, the Quadrupol study was limited, involving only four labs over a short period and offering little generalizable insight. While these exceptions are valuable, business-focused research in forensics remains limited, contributing to a gap between new scientific advancements and their practical implementation. Comprehensive business analysis, including cost-benefit assessments, is crucial for optimizing laboratory workflows [22]. A well-developed business plan should address five core areas: Strategic, Economic, Commercial, Financial, and Management Cases (HM [54]. This is illustrated below in Fig. 6.

Before any proposal can be made to improve the forensic provisions within a jurisdiction, a detailed understanding of the current business workflow is needed. For smaller jurisdictions, selecting the most effective forensic strategy requires an understanding of current challenges and opportunities, such as limited resources and infrastructure. In this case, potential benefits, risks, constraints, and associated dependencies for each workflow discussed in this paper (sample screening in a satellite laboratory, sample screening in a university, police laboratories and the

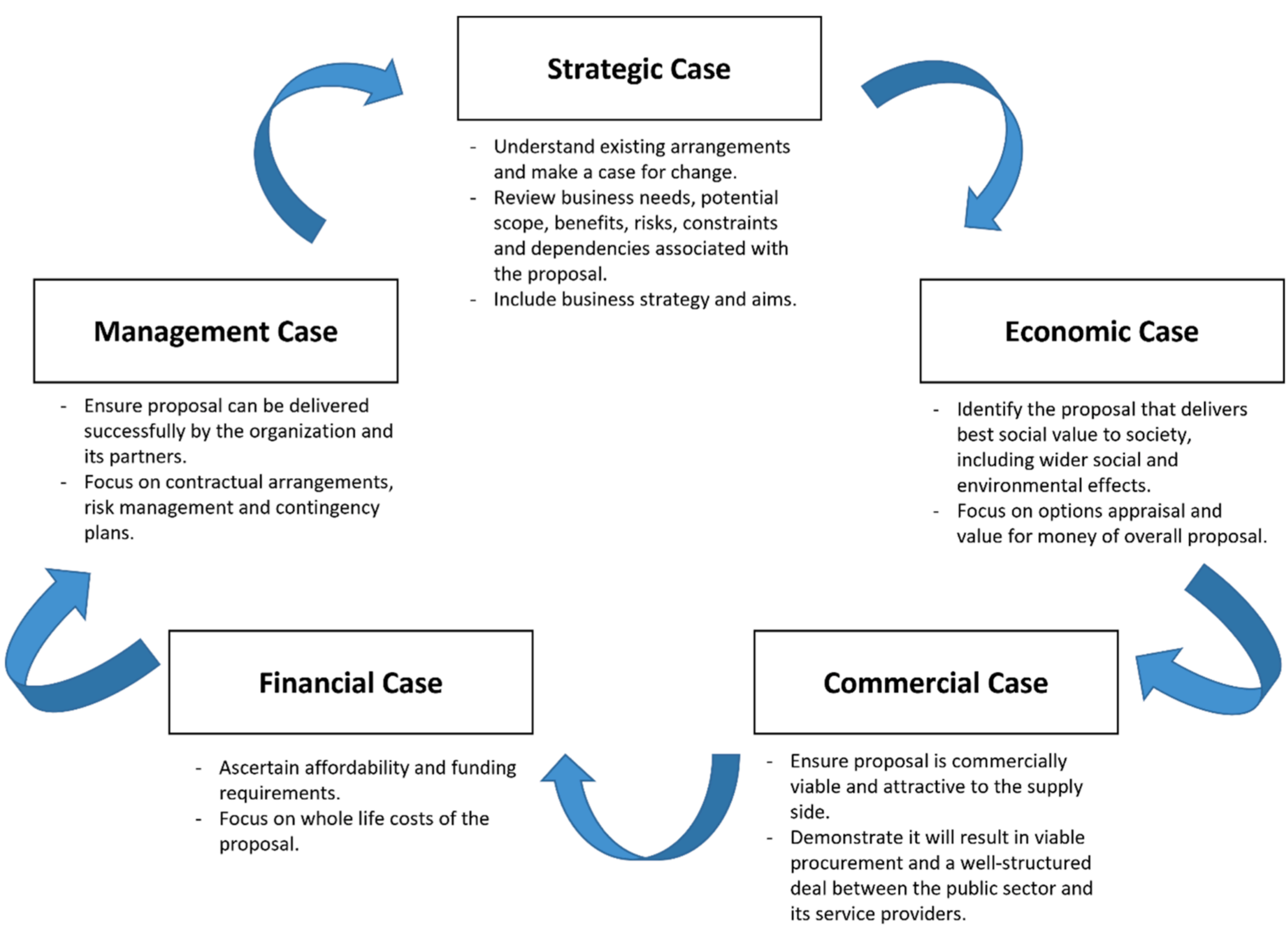

Fig. 6. A simple workflow on developing a business case following the Five Case Model recommended by the Welsh Government and the UK Office of Government Commerce.

Table 1
A visualization of the strengths, weaknesses and scope for improvements of the various laboratory pathways for forensic provision.

Workflow	Strengths	Weaknesses	Scope for improvements
Accredited satellite laboratory	– Reduce costs by outsourcing less. – Good QA means results accepted in court. – Quick quantification of DNA.	– Start-up and running costs are expensive. – Adds extra step for samples that may still require outsourcing. – Limited scope - only a small range of sample types could be analyzed. – Trained personnel may not be available locally.	– Potential to increase overall success rates by triaging samples. – Savings made from transport costs could be reinvested into various departments; emerging technologies, training staff, accreditation costs.
University laboratory	– Potentially cheaper analysis per sample. – Lower set-up costs. – Quick quantification of DNA.	– Results may not be admissible in court due to lack of accreditation status. – Lack of accreditation and control over quality assurance could lead to a lack of accountability and oversight.	– Potential for the introduction of more university courses. – Allows for teaching, research and experience opportunities.
In-house police laboratory	– Quicker process as less transport. – Great control over whole process. – Close working practices between police and lab increases flexibility.	– Lack of readily available infrastructure could make set-up expensive. – Could reduce the ability to produce impartial and objective results. – May be subject to societal scrutiny.	– Potential for the development of a stop at quant service. – Direct access to prospective novel research that could realize further improvements.
Rapid DNA	– Can provide fast results whilst suspect is still in custody. – User friendly.	– Due to sensitivity issues, it can currently only be used on reference swabs. – Due to high initial cost, if there isn't a high throughput of samples it may not be cost effective.	– With further research there is the opportunity to use on machinery on crime scene samples as well as reference swabs.

use of Rapid DNA technology), need to be acknowledged within the Strategic Case to build a compelling case for change.

The preferred option is that which proves its benefits outweigh the risks. For example, while an in-house laboratory might be ideal, the reality of funding constraints means alternative pathways, such as outsourcing or utilizing Rapid DNA technology, may be more feasible. In lieu of this, once scope for change is identified within the strategic case, a preferred option can be identified. With this, optimization begins to ensure the change in workflow would be of social value to the society, under The Economic Case. Routinely, a cost:benefit analysis is developed including setup costs, operational expenses, potential revenue streams and long-term financial viability, to identify the workflow that offers best social value to society. For example, the potential to carry out sample screening in a university or a hospital laboratory allows for the re-deployment of existing resources, including infrastructure and perhaps staff, this is classified as a non-cash releasing benefit to society. Both quantitative and qualitative data should be collected.

Moreover, commercial considerations, such as supply chain challenges in smaller jurisdictions, are essential. This requires an analysis of the forensic services market and an understanding of what could be achieved realistically by the supply companies as well as the procurement strategy and routes. The focus is the development and attainment of the most suitable workflow, which includes service requirements, contractual arrangements, and risk allocation.

The purpose of the Financial Case is to demonstrate the viability of the proposed workflow. This should assess capital and operational costs. Details of funding and confirmation of stakeholder support must be identified for the long-term affordability of the proposed workflow.

The Management Case ensures robust implementation, quality control, and risk mitigation measures are in place, including feedback into the strategic aspect, as illustrated in Fig. 6. Within laboratories, quality assurance and quality control are always top priority, therefore, the identification and assessment of potential risks, such as regulatory challenges, technological constraints, and operational uncertainties, needs to be addressed. The whole structure of the business, including risk management and contingency plans, contractual agreements, staff training programmes and resource allocation, must be arranged.

Table 1 exhibits advantages and limitations of the four potential pathways reviewed in this paper, as well as the scope they possess for future improvements.

When considering the Strategic, Economic, Commercial, Management and Financial case, in conjunction with knowledge on each potential pathway (as shown in Table 1), an informed decision can be made on the most suitable pathway.

A research article published in 2021 deduced the return on investment from Rapid DNA technology in the analysis of sexual assault kits in a forensic laboratory in Kentucky, West Virginia, USA [53]. It was reported that 'Rapid DNA technologies are a capital-intensive system' and it was found that the benefits yielded from this equipment far outweighed the costs. It was also highlighted that the research may be applied to other areas with 'limited jurisdictional budgets' which seems noteworthy in the case of small geographic areas. Similarly, there is literature identifying a $1677.75 per $1 return on investment simply by improving laboratory response time by just one day [60,59]. This could be an appealing argument in the previously discussed propositions of the implementation of satellite laboratories. Screening services or in-house analyses (as opposed to outsourcing) can significantly reduce turnaround times. Additionally, it has also been written in the literature that timely provisions can save resources and increase investigative accuracy. Moreover, employing screening services in conjunction with sample triage and Rapid DNA instrumentation can have the benefit of increasing suspect leads via elimination and inclusion and thus a quicker downstream analysis process [61].

Periodic performance assessments using industry-standard metrics, such as sample throughput or output per staff member, help identify areas for improvement and resource allocation [52]. This includes staffing, existing facilities, legislation and policies, geographic coverage, and finances [33]. These metrics can prove useful when identifying where resources should be focused, or which potential pathway discussed in this paper may be more suitable to the needs of that jurisdiction. Having quantitative data can become valuable in the acquisition of additional resources and funding.

Additionally, qualitative data, such as feedback from police forces or users of forensic services, can guide future developments. For example, surveys were used in multiple Australian forces when considering the implementation of Rapid DNA for reference samples in police charging stations [36]. This study found that where a case would benefit from the quicker turnaround time of results with using Rapid DNA, the impact would be substantial in that crime rates could reduce, and policing resources saved by repeat offenders being remanded in custody. However, the surveys identified that the use of rapid DNA could have only impacted the decision to release a suspect from custody in 0.6 % cases.

Ultimately, while there are a few examples of forensic research integrating business analysis, such as Project FORESIGHT and the limited Quadrupol study, the broader forensic science community has yet to fully embrace this approach. As the forensic landscape continues to evolve, more research is needed to close this gap and ensure that forensic strategies are not only scientifically sound but also financially viable and sustainable.

5. Conclusions

This paper reviewed the literature surrounding the potential of using various techniques to improve forensic services in resource constrained small jurisdictions. These included, the use of a satellite laboratory or hospital infrastructure, the use of a non-accredited laboratory such as a university for screening services, the alternative of using in-house police laboratories and lastly the enforcement of Rapid DNA technology. Where expenses may be reduced in one aspect, start-up costs for initial application can be high. On the other hand, a reduction in time to produce results and increased quality can allow for faster investigations and thus more cases which can have downstream effects on society and the judicial system. However, this juxtaposition of drawbacks and benefits further emphasizes the need for a comprehensive business case tailored to suit the needs of any specific area.

A satellite laboratory may be extremely beneficial at improving success rates by enabling sample screening and triage within the country. However, this could only be implemented if infrastructure were readily available. Assuming funds are the lacking aspect, set-up costs may be covered by the larger incorporation, if they are willing to expand. In this case it may be possible for their quality assurance measures and validation accreditation to also cover the satellite laboratory. A potential option was discussed as the use of hospital facilities where similar equipment for certain analyses may be accessible. Nevertheless, this would be of limited scope and there may be a lack of trained experts to operate the machinery in a forensic context. This idea was seen to work in Malta who carry out forensic pathology services at their university hospital successfully. Furthermore, the proposal for a non-accredited screening service was reviewed despite no previous literature being available in the context of smaller jurisdictions. It may be concluded that this would assist investigations by producing quicker results although without accreditation they could be susceptible to legal challenges in court. The potential of university laboratories offering screening services was explored and would prove to offer great societal value in terms of increasing accessibility for students to gain experience in the field as well as open the door to new research opportunities.

Where available, the ideal set-up would be dedicated forensic laboratories within the police station. This would entail minimum transport of evidence, reducing time to analysis and therefore minimizing chances of degradation of samples, which would in-turn provide better results at a faster rate. Increased flexibility and access to the laboratory process allows for greater control over the analysis of samples and their prioritization. The potential for increased communication between the laboratory and the police offers would allow for a smoother pipeline. However, this route would require funding and expertise that resource constrained small jurisdictions do not tend to have in excess. Moreover, the use of Rapid DNA technology was explored due to its multitude of applications in various scenarios. Fieldwork examples were mentioned but there was an overall conclusion that at this time Rapid DNA is only available for the use of reference samples, which could still prove to benefit smaller countries.

Ultimately, all potential solutions described have beneficial aspects that may enhance forensic services in areas where resources are scarce. However, the best route cannot be deduced without first identifying specific goals and an analysis of current infrastructure, finances, resources and crime rates. Only then can a complete business plan be fabricated to determine which pathway is ultimately feasible and most favorable. It is also worth noting that forensics worldwide is still a discipline severely lacking in funding and so difficulties experienced by laboratories in general will only be enhanced in those countries that further lack resources.

CRediT authorship contribution statement

Jason Birkett: Writing – review & editing, Supervision. **Cynthia Akwei:** Writing – review & editing, Supervision, Methodology. **Anabella De la Chica:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **David Lamont:** Supervision, Methodology. **Nick Dawnay:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition.

Declaration of Competing Interest

None

Acknowledgements

This research was carried out as part of a PhD project funded by the Gibraltar Department of Education in collaboration with Royal Gibraltar Police and the Gibraltar Health Authority.

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